THE ELEMENTS OF ECONOMIC GEOLOGY

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BY

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PREFACE

THE different sections of Economic Geology are intimately connected. Thus some ore deposits are dependent on deep-seated solutions and others on coastal action, the characteristics of soils illustrate rock decay and the circulation of underground water, earthquakes connect superficial and plutonic action as they arise from faulting at the depth of hundreds of miles, and the problems of water supply show that the surface is nourished by new material from the interior. Hence it is convenient to consider together the various branches of civil and mining engineering and of agricultural geology. To cover so varied a field in a short book renders necessary omission of reference to some metals that throw no special light on general principles, and to some agencies and processes that are adequately dealt with in geological text-books. The examples chosen illustrate various principles and processes, the selection being often determined by my having had the privilege of examining them personally.

The literature of the Economic Geology is now so overwhelming, that reference to it has had to be sternly limited, or it would have taken an undue share of the space ; no reference has been given to much of the better-known literature, the references given being to those that would be useful to students, or to the authorities for evidence relied on in the conclusions adopted.

I may refer here to a few convenient sources of information, such as the monographs on useful minerals and ores by the Imperial Institute, to the statistics in the annual volumes of *Mineral Industry ;* for the original literature on the ores of North America, which are often mentioned in the text, to W. Lindgren's *Mineral*

Deposits (1913); for the bearing of physical chemistry on the formation of mineral deposits to Dr. R. H. Rastall's recent *Physico-Chemical Geology*, and for the processes of rock formation to *The Principles of Petrology*, by Dr. G. W. Tyrrell, a colleague to whom I am indebted for much help in the preparation of this work.

Theories of ore formation still show great but not unnatural differences of opinion; the conclusions stated in this book differ from those of some standard works by regarding more ores as due to the deposition, solution, and redeposition of sedimentary metallic grains, and by accepting fewer ores as due to direct igneous processes; and also by regarding the source of most metals as an ore-zone beneath the ordinary igneous rocks of the crust and not the igneous rocks themselves. Twenty years ago I put forward explanations of some fields on those lines, which were opposed by most of the authorities; but opinion has since changed, and the extension of these conclusions may be expected to some other fields. Some of the authorities whose opinions are not adopted may feel that their conclusions have been dismissed too briefly; but the need for brevity has prevented the full statement of the case for either side. The apparent discourtesy of the dismissal of eminent opinion without due notice is the discomfortable fate of those who write brief text-books on wide subjects. "A tale has seven variations, and all cannot be told if time is short," was the tactful remark with which my East African headman once explained away a misunderstanding; and the infinite variety of subjects with which Economic Geology deals, and the ambiguity of much of its evidence, give equal variability to the solution of its problems. If the book had been twice as long some views would not have been rejected with the apparent dogmatism rendered necessary by the limitations of space.

J. W. G.

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November, 1927

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ABBREVIATIONS

G.S.	Geological Survey, as in U.S.G.S., United States Geological Survey.
Mem. G.S.	Memoir of the Geological Survey of . . .
Min. Dep.	Mineral Deposits.
Min. I.	Mining Institute . . .
Ming. Mag.	Mining Magazine.
Miner. Mag.	Mineralogical Magazine.
N.J. Min.	Neues Jahrbuch für Mineralogie.
N.S.W.	New South Wales.
Q.J.G.S.	Quarterly Journal of the Geological Society (London).
Tr. I.M.E.	Transactions Institution Mining Engineers.
Tr. Amer. I.M.E.	Transactions American Institution of Mining Engineers.
Tr. I.M.M.	Transactions Institution of Mining and Metallurgy.
Z.d.g.G.	Zeitschrift deutschen geologischen Gesellschaft.
Z. prakt. G.	Zeitschrift für praktische Geologie.

The rest are obvious from the above.

Tons are long tons (2240 lb.), unless otherwise stated.

THE ELEMENTS OF ECONOMIC GEOLOGY

PART I

INTRODUCTION

CHAPTER I

THE SCOPE OF ECONOMIC GEOLOGY, AND THE SEARCH FOR ORES

Economic Geology applies the principles of geology to the study of the useful materials in the earth's crust, and to the investigation of their origin and distribution so as to help mining to its ideal—the working of minerals at the least cost and with the greatest profit. How effective geology may be is shown by the statement by J. E. Pogue in his *Economics of Petroleum* (1921, p. 343) that of an extensive series of American oil-well records, 85 per cent. of the wells sunk in accordance with geological advice proved successful, whereas of those sunk at random, only 5 per cent. were productive. The chief minerals with which the economic geologist has to deal are building stones, slates, and marbles; the materials used for cements, the clays for pottery and bricks, and sands for glass manufacture and moulding; the mineral fuels, including coal, mineral oil, and peat; the mineral bitumens; the minerals used as fertilizers, including phosphates, nitrates, potash, and lime; various minerals of service from special physical and optical qualities, such as micas and gems; the sodium and potassium salts; the ores which furnish the metals indispensable to a civilized community, and the pure water necessary to its health. In addition to the study of these materials, the economic geologist is concerned with the arrangement of rocks to facilitate their quarrying, with the protection of coasts from attack by the sea, of plains from devastation by rivers, of harbours from shoaling, and of buildings from overthrow by earthquakes, with the avoidance of hidden dangers in the selection of reservoir sites, and the maintenance of public health by the utilization of underground water and safe methods of drainage.

The problems of economic geology are complex owing to the multiplicity of the materials, the variability of local conditions, and the influence of prices and costs. A material which in one place may be a valuable ore in another may be commercially worthless. Profitable use is an essential factor in the definition of the term ore. An ore is a material containing sufficient metal to be worth mining under conditions which either already exist at the locality, or may be reasonably expected.

Mineral—This term is used with two different meanings. Mineral in the general sense is any inorganic material, and includes animal and vegetable products which have been buried in the earth and become part of its crust. Some geologists limit the term to materials which have a definite chemical composition, and usually a regular crystalline shape, and regard coal, slate, limestone, mineral oil, oil shale, and most ores as not minerals. The aim of this inconvenient definition is to emphasize the distinction between simple minerals and rocks. Before about 1850, rocks were regarded as minerals; the first editions of Dana's *System of Mineralogy* included a chapter on "Rocks or Mineral Aggregates." Lyell (*Principles of Geology*, 7th ed., 1847, p. 784) distinguished between "simple minerals" and mineral aggregates. Minerals were divided into two sections; simple minerals, or mineral species, such as quartz and felspar, cannot be divided into simpler constituents without chemical decomposition; compound or mixed minerals may be separated into their components mechanically, as granite can be separated into its three mineral species, quartz, felspar, and mica, by crushing and sorting the fragments. As academic mineralogy developed it was limited to the study of mineral species, and most compound minerals were left to the branch of geology known as petrology. Leading British mineralogical authorities define minerals as "inorganic materials." The British Museum (*Introduction to Study of Minerals*, pp. 1-2) adopts as mineral "the unorganized products of our own Earth" and of outer space, including soil and rock. Sir Henry Miers (*Mineralogy*, 1902, p. 1) defines as mineral "the materials which constitute the solid crust of the earth," and refers to granite and coal as minerals. Coal, petroleum, slate, and ironstone are not "mineral species;" but they are minerals according to legal and commercial usage, and to leading mineralogists. The definition which asserts that most branches of the mining industry and of economic mineralogy are not concerned with minerals is more paradoxical than sagacious.[1]

ORE-GRADE—The student of economic geology has to consider the commercial value of minerals, which depends on many factors, including accessibility to a market, the cost of working, the price of the useful constituent, and its chemical condition, and the grade of the ore. Deposits containing large supplies of useful mineral in positions remote from markets may be useless owing to the cost of transport. A material containing less than 1 per cent. of copper may be valuable if the copper be native, but not if it be a sulphide that would require smelting. An iron ore may be worthless if it contain less than 50 per cent. of iron; whereas an ore may be valuable with 1 part of platinum in 100,000 parts, and alluvial beds have paid to work that yielded 1 part of gold to 15 million parts of dross. Price has therefore to be considered in connection with all economic minerals. Hence in the chapters dealing with ores, facts are stated as to the range of price of the metals.

METAL—The term metal is not used in economic geology in its chemical sense, but with the general meaning of opaque substances which have a bright lustre, can be melted, and are usually heavy. Calcium, sodium, and potassium, which are metals according to chemical terminology, are regarded by the economic geologist as non-metallic. He regards most ores as consisting of metallic and earthy constituents,

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[1] For further definitions see "What is a Mineral?" *Tr. I.M.E.*, 1909, vol. xxxvii, pp. 13-42.

and in the latter includes some constituents, which the chemist classifies as metallic.

The economic geologist has two special difficulties in addition to those which attend other branches of geology. Mining destroys the ores and the evidence as to their formation. A shallow mine may work out a body of rich ore and remove the clues to its extension underground and its method of formation. Unless the evidence as to the origin of an ore is recorded and samples preserved while it is being worked, its contribution to the genesis of ore deposits is lost for ever. The second difficulty is the unusual complexity of the problems; their treatment by rule of thumb often ends in financial loss or structural disaster. Each problem must be investigated by reference to the principles of geology, of which sound knowledge is indispensable in the economic applications of the science.

The Sporadic Distribution of Ores—The first striking feature in the study of ores is their scarcity. They occur as small bodies, separated by wide oreless interspaces. The patches of ores may be so small that if marked on a true scale they would be barely visible on a map of the country. West Australia owes its development to its rich ores; but they occur at widely scattered localities. The United States is predominant in the supply of copper. It has often yielded over 60 per cent. of the world's output; and of this amount, in 1895, nearly half came from an area of 2 square miles at Butte City. The world was long dependent for aluminium upon a single vein of cryolite in southern Greenland, for potash upon central Germany, for nickel on New Caledonia until Sudbury in Canada shared the monoply, for mercury on the mining fields of Almaden in Spain, Idria near the head of the Adriatic Sea, and California, and for platinum on the Ural Mountains.

This sporadic distribution of the mining fields is repeated on a smaller scale for the ore within them, which may be limited to one vein or ore-body, and perhaps to a small part of one vein; while many neighbouring veins though apparently similar may be barren.

Prospecting—The sporadic distribution of ores may appear at first sight to render their discovery possible only by accident, and some important mineral fields were thus found. The nickel ore of Sudbury and the silver veins of Cobalt were both cut during railway construction. Nevertheless most important mining fields have been discovered by systematic search. When a mining prospector visits an unknown country he would regard iron ore, coal, oil shale, or ordinary earthy minerals as useless until the country has been settled; he would look for gems and the more valuable metals, such as gold, platinum, tin, and copper. His search would usually begin by examining the local gravels. If their pebbles consist of unaltered limestone or sandstone the indication would be unfavourable; but schists, traversed by quartz-veins, and abundant quartz pebbles would be encouraging. The prospector would use a "tin-dish" which is a basin of tinned iron with a flat base, and a rib on one side. The usual size is 16 to 20 inches in diameter at the top, 10 to 12 inches at the bottom, and 2½ to 3 inches deep; it holds, when heaped up, about 20 to 25 lb. of earth, which is washed by pouring water into the dish, stirring the gravel by hand and throwing aside the pebbles as they are cleaned of sand and mud. The prospector pours out the water as often as it becomes muddy, and at the same time gets rid of the fine sand until only the heavier material is left. This residue is spread by a flow of water along one side of the floor of the dish; the constituents are left in a streak in order of their specific gravity, the heaviest at one end and the lightest at the other. If gold is present it is conspicuous by its bright color, and as, owing to its malleability, tiny particles are hammered into broad flakes which are known as *colors*. They are too small to be weighed in the field, but on an average 35 "colors" weigh one grain. As the tin dishful is from $\frac{1}{150}$ to $\frac{1}{180}$ of a cubic yard the prospector, by counting the colors, can calculate the amount of gold per cubic yard or ton. The other materials in the residue would probably include crystals of zircon, heavy silicates, and grains of "black sand," i.e. oxide of iron. The glassy grains would be examined for gems, and would be tested by pressing beneath a piece of wood against a piece of glass or quartz. If a grain scratches quartz it is probably one of the gems.

If this washing yielded nothing of value the prospector would follow a river inland, testing the gravels along its course. Any colors of gold would be recorded on a sketch map, and they would increase in size and number toward the source of the gold. Where the colors are abundant some grains of gold would probably be found, and perhaps ovoid particles with a spiral mark ; they, from their resemblance to the dung of mice, are known as mouse-droppings. They are due to a grain of gold having been hammered by pebbles into a thin disc, which has been coiled up as it rolled down stream ; the outer edge of the disc forms the spiral mark. Coarse angular grains are called *shed gold* because it is thus shed from the parent rock. Owing to the softness of gold the grains are soon worn smooth, so that shed gold has not travelled far. If no gold or only a few colors are found beyond a place with shed gold, the prospector infers that he has passed its source, and would search for a "lode" from which the gold may have come. The most likely lode would be a vein of quartz ; and any quartz-veins would be examined, especially if the quartz contained cavities and were stained brown by oxide of iron.

If no rock is exposed the search is continued by *loaming*. The prospector has a long cotton bag, perhaps 6 feet long and 6 inches in diameter. He digs a regular series of holes and places a sample of earth from the bottom of each in the loam-bag and ties a string just above each sample ; the process is repeated until the bag is full, when it resembles a string of sausages. The loam-bag prevents any mistake in the order of the samples, which are washed one by one in the tin dish at the river side. The results are marked on a plan which shows the distribution of the gold. A line could probably be drawn on the plan separating the gold-bearing from the barren samples. The source of the gold should lie near that line. The prospector would next search for the lode by *costeaning*, a Cornish term for open trenches, or, if the material be too deep, by a line of pits. The "costeans" would be dug to the bedrock, and should expose the lode from which the gold has come. The lode would be sampled to determine whether it is rich enough to repay working, or whether, until the country has been settled, it would be more profitable to work only the alluvial material.

During this prospecting if other valuable metals are present in the district traces of them should be found, such as grains of tin ore, which would probably be associated with fragments of black tourmaline (schorl) and topaz. If the miner has failed to find in the alluvial beds any gold, platinum, tin, or gems, he would turn to the hills or areas of exposed rock in the hope of finding other minerals. He would search for quartz or calcite, and in them for metallic minerals, which in most veins would originally have been sulphides. In a moist climate the sulphides near the surface are oxidized and removed in solution. Some of the iron would probably have been deposited as iron oxide, staining the vein brown or red. Sulphides of copper would have been dissolved, and possibly redeposited as the green carbonate, malachite, or as plates or strings of native copper. If the vein contained lead the top of the lode would probably contain cerussite, the carbonate of lead.

Iron-bearing lodes and seams of coal and oil shale would be noted as resources available for the future. Lodes containing the precious metals or the more valuable of the base metals, copper, lead, zinc, nickel, etc., would be prospected to determine their grade or proportion of valuable constituents.

Structure of Lodes—The simplest form of lode is a metalliferous vein traversing the bedrock, which is technically known as the *country*. Veins are sheet-like in form and range from horizontal to vertical. Each lode or vein is bounded by two walls or *cheeks*, of which the upper is known as the *hanging-wall*, and the under as the *foot-wall*. The horizontal direction of a vein is its *strike* or course. The inclination from the horizontal is the *dip* (Fig. 1); the inclination from the vertical is usually the more useful measurement, and is the *underlay* or *hade*. A lode may consist of a single vein or may be compound. A compound lode consists of a series of veins, either of the same or different materials; the veins may be parallel, or divergent, or in a network, or may be mixed with masses of broken country. The simplest lodes are those deposited in fissures, which are of two chief kinds. The first are clefts of which the walls have been pulled apart

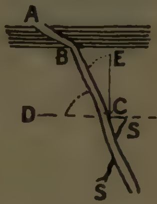

Fig. 1.—Diagram of a Lode.

AB, strike; BCD, dip; ECB, hade; S, spurs.

by tension, as when a sheet of rock is stretched by folding, or shrinks during cooling or drying. The second kind of fissures are formed along faults, i.e. where the rock on one side of a fracture has been moved along it. Faults are usually marked by *slickensides* or scratches on the walls, and by a rubble of rock fragments known as fault-breccia. *Pug* or *fluccan* (Cornish) or *gouge* (American) is material that has been ground by the movement into clay. Faults are usually not quite straight, but curve around harder layers or masses. Owing to the curves the fault fissure usually consists of lenticular spaces, separated by the projections of the opposite walls coming into contact. The lode or vein along such a fault alternately expands and contracts and may consist of isolated lenticles of ore. A lode in which the sides are not parallel is known as a *block-lode* or *wavy-lode* (Fig. 2); where the lode widens it is said "to make;" where it contracts it is said to "pinch" or "peter." The thin streak along part of a fault plane on which there may be no lode matter, except perhaps a film of pug, is said to be the "lode track," as the miner expects it to lead him to the next "make" of ore. If a fault crosses a series of bedded rocks the fractures may be diverted here and there along a bedding plane, and the lode may therefore be repeatedly deflected and may consist of steps; such *step-lodes* may be due to a series of faults. Either the part along or across the bedding plane may be represented by a *lode track*, and the actual lode be reduced to a series of parallel isolated sections.

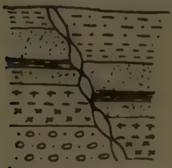

FIG. 2.—A WAVY-LODE.

A wavy lode formed along a fault in the spaces left between the projecting harder rocks.

A vein parallel to the bedding of the rocks is a *bedded-vein;* a vein transverse to the country, if confined to one bed, is a *gash-vein*, but if it cut across several beds, it is a *rake-vein*.

Lodes are usually steeply inclined; if horizontal they are often known as "floors." If formed along more or less horizontal faults they are sometimes known as "slides." Floors often occur one below another in a dyke or narrow intrusion of igneous rock; these floors are formed along horizontal fissures due to the shrinkage of the rock during cooling. The floors are arranged like the rungs of a ladder, and such lodes are called *ladder-lodes* (Fig. 3). The typical examples are at Wood's Point in Victoria, where they occur in dykes of hornblende-porphyrite in slate. As a rule the floors of a ladder-lode are confined to the igneous rock; but where on solidification that rock froze firmly to the adjacent slate the shrinkage cracks and consequently the quartz-floors extend into it.

Contra-lodes (Fig. 4) are small lodes which cross a lode at a high angle, just as great faults are crossed by secondary cross-course faults. If some lode material has been deposited along a cross-fault it is a *metalliferous cross-course* or contra-lode; if the cross-course be only filled with clay it is a *cross-fluccan*. Great faults may extend to depths of probably a hundred miles, and the fissure lodes doubtless extend far below the levels which can be reached by mining; and some lodes, or series of associated lodes, may extend for hundreds of miles in length.

FIG. 3.—A LADDER-LODE.

A ladder-lode in a dyke traversing slate. In two cases the quartz-floors are shown penetrating along cracks into the slate.

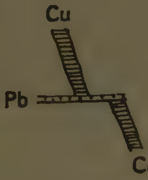

FIG. 4.—A CONTRA-LODE.

A contra-lode (Pb) containing lead, formed along a fault which has broken a copper lode (Cu).

Lodes are usually much longer than their thickness; but those formed along the intersection of two fractures or in a solution channel are *pipe-lodes* or "ore chimneys," as the Achilles lode of gold ore at Tarradale, Victoria, or the Harrington-Hickory Mine in Utah due to the replacement of limestone along a cross fissure by lead ore (Butler, *U.S.G.S.*, *Prof. Pap.*, 111, 1920, p. 517).

Lodes in folded sedimentary strata are often isolated, and some are saddle-shaped in cross-section. When alternate beds of slate and quartzite are bent into parallel anticlines and synclines, lens-shaped spaces are apt to occur along the top and bottom of the folds. The spaces taper out on the sides, as the beds are there forced together by the lateral pressure which caused the folding. Percolating water will deposit material in the spaces and thus form lodes which are thickest at the crown or cap of the arch, and thin out on each side (Fig. 5). These formations are *saddle-lodes* and are best known in Bendigo, Victoria. The crown in those at the surface had been destroyed by denudation leaving two sheets of quartz dipping in opposite directions. As these sheets thinned out at a slight depth it was feared that the mines would be shallow, as search for isolated patches of quartz would be too costly. The regular distribution of these bodies on the arches of the anticlines was proved during the survey of the field by the Geological Survey of Victoria, and as similar arches of quartz were found one below another along the anticlinal axes, mining was carried to the depth of 4,500 feet. Bendigo, instead of being merely a superficial field, included for a time the deepest gold mines in the world. Lodes are also found on the floors of synclines; but these "inverted saddles" are less rich in gold than the anticlines, though they have been profitable, as at Wedderburn.

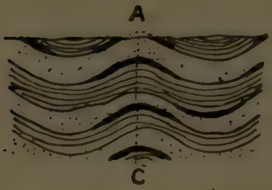

FIG. 5.—A SADDLE-LODE.
A saddle-lode with quartz saddles between quartzite and slate. One inverted saddle is shown.

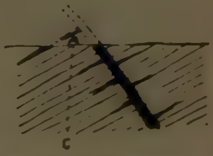

FIG. 6.—A FALSE SADDLE.
A false saddle-lode due to spurs along the bedding planes from a main vein. The line AC of the assumed "centre country" would lead away from the ore veins.

As saddle-lodes occur one below another it is important to distinguish between true saddle formations and "false-saddles." Adjacent lodes may dip in opposite directions like the two limbs of a saddle-lode that has lost its cap; and if the two lodes were the flaps of a saddle other saddle-lodes would be expected below. False-saddles may be due to the occurrence of a bedded vein near a rake vein; either of them may be the main lode and the other the branch. The search for an underground repetition of this structure should be made along the major lode, and not along the plane bisecting the angle between the two lodes (Fig. 6).

Lodes sometimes bifurcate into approximately equal divisions, but they more often give off branches or *spurs* (cf. Figs. 1, 6). The branches may be small and are then known as "stringers." Those on the hanging-wall of a lode are often described as "leaders" or "feeders," on the view that they fed the lode; those on the footwall are called "droppers."

In some fields that have been broken by intersecting fractures the quartz-veins form an irregular network; the veins may divide and reunite, or disappear irregularly.

Lodes are often formed along fissures, as they are channels for the passage of metalliferous solutions. As the solutions cool they deposit some of their constituents on the walls of the fissure; crystals thus formed are often prismatic, and they grow crowded and parallel like the teeth of a comb; each sheet with this "comb structure" is known as a *crust*. The successive crusts may be of different materials, and may fill the fissure or leave only a thin median space known as the *vugg*. Crustified lodes are formed by the gradual infilling of a fissure from solutions. The fissure may be enlarged by repeated earth-movements, and thus a thick lode may be formed of numerous crusts. They may be symmetrical on the two sides, but, especially in the case of moderately inclined lodes, the one side may be thicker, and have more crusts than the other. The Three Princes Lode at Freiburg in Saxony at one part consisted of twenty crusts, which in order from the outside were blende, quartz, fluor, blende, barite, pyrites, barite, fluor, pyrites, and calcite, with a central vugg. This sequence indicated repeated variations in the temperature and composition of the solutions which deposited the lode.

A lode is not always sharply marked off from the country, for the solutions may have impregnated the wall rock with the lode minerals.

Lodes consist of earthy minerals or veinstones, of metallic constituents, and of fragments of country rock. The commonest veinstone is quartz. Next in importance is calcite, which is especially abundant in limestones. Fluorite, barite, and dolomite are frequent in volcanic regions, and in deep-seated lodes. Less common are the felspars, rhodonite (a pyroxene composed of silicate of manganese, $MnSiO_3$), and garnets. Tourmaline, usually in the black variety known as schorl, and topaz are common in lodes that have been formed by superheated acids. Mica of economic value occurs under similar conditions. The metallic constituents sometimes form a minute proportion of the lode; but they give it its special character and value. The metals are sometimes native, but are usually present as compounds, chiefly sulphides, oxides, and carbonates. The fragments of country in the lode may have fallen into the fissure, or have been torn from the walls by the faulting, or be parts that resisted replacement by the lode-forming waters. Large masses of country rock in a lode are known as *horses*. That terms is sometimes applied to the country between two arms of a branching vein, and also to beds of sandstone which have filled stream channels in coal. The term "horse" is conveniently restricted, in connection with a lode, to the original meaning of a mass of country which is completely surrounded by the lode.

The veinstones and rock debris found in a lode are sometimes grouped together as "gangue," a French form of the German word "gang" which means the whole lode. The rock debris in a lode is known in Australia as "mullock;" the term has been rejected as miner's slang, but as it was similarly used by Chaucer, that objection is invalid. Some lodes consist of a fault-breccia of mullock, with the interspaces filled with veinstones and metalliferous constituents. True brecciated lodes have been broken into fragments by faulting or pressure after their formation.

THE TERM REEF—There is much confusion between the terms reef and lode due to a reversal of the meaning of reef. Owing to the heaviness of the metallic grains the richest layer in an alluvial mine is usually at the base. When all the material above the bedrock has been worked out the mine has reached its end as surely as striking a reef is fatal to a ship at sea. Hence the Australian miners referred to the barren rock beneath the gold-bearing deposits as the reef, and the term is still so used in alluvial mining. In some mining fields it has come to mean the opposite; for after the alluvial deposit had been worked out the miners searched for the source of its gold in the quartz-veins in the bedrock; they distinguished these veins of quartz from the pebbles of alluvial quartz as "quartz in the reef" or "reef-quartz," which were in time abridged or reversed to quartz-reef.

The long-established term for ore-veins is *lode*, which has been used in Cornwall, and by Chaucer and Shakespeare. The word has the same origin as "to lead" and as "leet," a channel of water. A lode leads the miner along the course of the ore. When gold mining began in California in 1849 the term lode was adopted and is still used there, as in "the Great Mother Lode." The equivalent term in German is "gang" from the verb to go, and has the same meaning. In South Africa, on the other hand, the term reef was adopted for the lodes, instead of for the country rock, and this practice has been extended in recent years. In some fields the term reef has been used in the two opposite senses, for bedrock in regard to the alluvial deposits, where the "reef drive" is the main drive through the bedrock; while lodes in the bedrock are known as "reefs." It would be well, where local practice permits, to retain lode for sheets of ore, and reef in its original meaning for bedrock.

CHAPTER II

THE FORMATION OF DEPOSITS OF USEFUL MINERALS

THE sparcity and local distribution of ores (cf. p. 4) suggested to the earliest students of ore deposits that they must be formed under exceptional conditions. The sea contains in solution most of the metals that are found in the crust; but if the ores were derived from sea-water, as has often been suggested, they should be more widely distributed in marine deposits. Most ores do not occur under conditions that indicate a marine origin. Tin is associated with hot acids appropriate to great depths below the earth's surface, mercury with rocks shattered and displaced by mountain-forming movements, and primary gold with igneous intrusions.

HISTORY OF STUDY OF ORES—The scientific study of ores was begun in southern Germany. In the eleventh century the chief mines in Europe were those of lead and silver in the Harz Mountains in central Germany. The tyranny of a local duke drove some miners to Saxony, where in 1160 they founded a free settlement—Freiberg. They there discovered mines richer and with more varied metals than those of the Harz; the district was called the Erzgebirge (Ore Mountains), and the working of its complex ores laid the foundations of modern mining and metallurgy. These ore-veins descend steeply into the earth and as a rule become poorer and thinner and subdivide downwards. As in the human body many veinlets collect the blood and lead it into the main veins, so the veins of ore were attributed to many veinlets having collected some metal-bearing fluid on its ascent through the earth's crust. Agricola (*De Re Metallica*, 1556) established the first scientific mining school when he showed that lodes were deposited from solutions in fissures; his followers were "ascensionists," as they attributed the ores to metal-bearing emanations due to

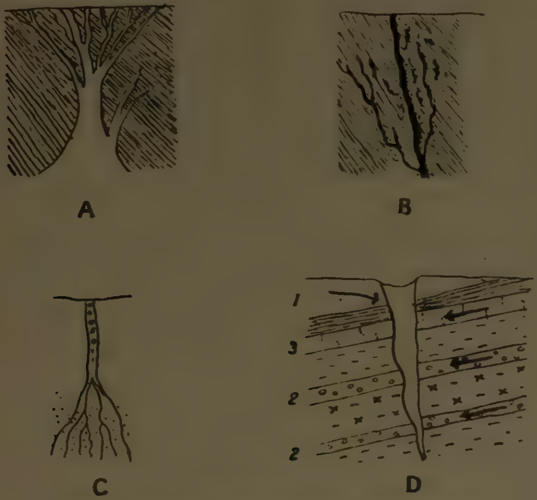

Fig. 7.—Early Theories of Ore Genesis.

A-D. The development of early theories of ore genesis.

A. The early Ascensionist School from Bauer, 1496, to Lehmann, 1753, the veins being attributed to injection from the interior of the earth.

B. Von Trebra, 1785, the lodes being due to deposition from solutions which have risen from below along fissures and have also impregnated the adjacent rocks widening the lodes by "transmutation" (replacement).

C. Lasius, 1789. The ores derived by the solution of metallic particles by widespread ascending water which collects into one channel and deposits the ores along its course.

D. Werner, 1791. Lodes formed in a fissure which ends downward and is filled by water from the porous beds. 1 and 2, sandstone and grit, 3, limestone, from which are derived the ores and veinstones in the fissure.

"fermentations" in the bowels of the earth (Fig. 7). Lehmann, in 1753, pointed out the upward branching of veins and that their crystalline character indicated deposition from hot solutions; he attributed lodes to "lapidific juice," rising through the crust-like sap in a tree. Lasius, in 1787, explained the ore solution as widely diffused ascending water (Fig. 7) which dissolved scattered grains of metals in the rocks through which it passed. Henkel (1679-1744), "the Father of Mineral Chemistry," recognized the evidence for the formation of lodes by replacement; but in accordance with the terminology of his time called it transmutation. Werner, the founder of the modern Freiberg school, in 1791 repudiated all theories based on transmutation, insisting that intransmutability is "the fundamental pillar of chemistry;" he claimed, like the lateral secretionists, that as lodes become poorer and thinner below, they must be filled from above or from the sides. These early students of ore deposits recognized facts which have only been duly appreciated within recent years, and their view of the ascensionist origin is now established for most lodes, though the ores of iron and manganese are mainly due to water that is percolating downward.

STRUCTURE OF THE EARTH; ITS BARYSPHERE—The metals in the ores were originally scattered through the primary material of the earth. The largest part of the earth is the barysphere, a shell more than 3000 miles thick, and composed mainly of iron alloyed with nickel.[1] The core of the earth, the centrosphere, about 1600 miles in diameter, is fluid as it does not transmit waves of distortion due to earthquakes. The rocky crust, the lithosphere, for which the phenomena of earthquakes and radioactivity suggest a thickness of about 40 miles, may be regarded as a slag due to the lighter materials having floated upwards, while the heavier constituents sank and formed the barysphere. The weight of the earth shows that the bulk is metallic, and its constituents, in order of abundance, are probably—iron, oxygen, silicon, magnesium, nickel, calcium, and aluminium.

The lithosphere was formed primarily of igneous minerals, which solidified from a molten state. They gave off during their consolidation water and gases which form the two outer layers of the earth, the hydrosphere or the surface waters, and the atmosphere. The action of water and air and sudden changes of temperature break the surface of the lithosphere into fragments which are deposited as beds of

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[1] For fuller information, cf. Tyrrell, *Principles of Petrology*, pp. 4-7.

sand and clay. Some constituents of the lithosphere are deposited chemically or organically in such beds as gypsum, salt, limestone, coal, and ironstones.

The barysphere doubtless passes to the lithosphere through an ore-zone, rich in silicates and metallic sulphides. Above the ore-zone is a basic zone composed mainly of heavy silicates, and known as the sima from the first letters of its chief constituents, silica and magnesia; still higher is an acid-zone of light silicates, with much alumina and alkalis; it is known as sial, from the symbols of silicon and aluminium. The upper part of the lithosphere would probably at first have contained but few metals. The metallic constituents of the barysphere, ore-zone, and sima have been raised to the surface by the intrusion of basic igneous rocks, which have carried upward large quantities of iron and manganese, and facilitated the ascent from the ore-zone of mineralized water.

Source of the Metals in Ores—Some species of pyroxene, amphibole, and olivine contain iron and manganese as essential constituents; and as metals in nature are seldom pure it is not surprising that small quantities of copper, cobalt, and nickel are found in ferro-magnesian minerals. The search for various metals in igneous rocks was inspired by the theory of Bischoff (1847) that the contents of lodes are derived from the rocks beside them by lateral secretion. His disciples, such as Forchhammer (1855) and F. Sandberger (1882 and 1885), claimed to have found all the common metals in the minerals of igneous rocks. Thus olivine, augite, and hornblende yielded Sandberger arsenic, bismuth, cobalt, copper, lead, nickel, tin, uranium, and zinc; and the micas yielded arsenic, bismuth, copper, lead, tin, uranium, and zinc. Many later chemists[1] have reported traces of the less common metals in igneous rocks. Some of these claims are dubious, as the amounts are too small for reliable determination. In other cases the elements have been introduced after the formation of the rock and are secondary constituents; e.g. the oft-quoted gold in the diorite of the Ayrshire Mine,

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[1] E.g. copper in fresh olivine dolerite in the Globe district, Arizona; Ransome, *U.S.G.S.*, *Prof. Pap.*, 12, 1903, p. 128; J. H. L. Vogt estimates the amount of nickel as ·03 per cent. in gabbros and norites, and ·0005 per cent. in granite, *Econ. Geol.*, xviii, 1923, p. 328.

Rhodesia, has replaced (*Tr. I.M.E.*, xxxi, 1906, p. 85) ilmenite. Although the ferro-magnesian minerals probably contain small amounts of other metals besides iron and manganese, it is only where igneous rocks have undergone strong secondary changes that the less common metals occur in workable quantities. These ores are secondary constituents of the rock. Dr. A. Brammall gives reference to literature in favour of the primary occurrence of gold in igneous rocks; but in the two cases he describes the gold is found with vein-quartz and such secondary minerals as tourmaline (*Miner. Mag.*, xxi, 1926, pp. 15-16).

ORE FORMATION IN RELATION TO IGNEOUS ROCKS—The discovery of many metals in igneous rocks and of these rocks in most important ore-fields led to the lateral secretion theory giving place to the view that the metals in most lodes are derived from particles present as original constituents of igneous rocks. This dependence of ores upon igneous rocks was widely adopted after a paper by the late J. F. Kemp on "The Role of Igneous Rocks in the Formation of Veins" (*Tr. Amer. I.M.E.*, xxxi, 1901, pp. 169-98) which is one of the classics of mining geology. Igneous rocks are undoubtedly the source of the iron and manganese in many ores. The theory was extended to the ordinary lode metals—gold, platinum, silver, copper, tin, lead, zinc, nickel, cobalt, etc., of which igneous rocks are either barren, or contain only minute traces that may be secondary. There is no *a priori* reason why copper should not be a primary constituent of ferro-magnesian minerals; but as among igneous rocks it is most often found in diabase, using that term in its English sense, it occurs in altered rather than in fresh rock. Gold is found in diorite and porphyrite, where the rock has been altered to propylite or by the development of chlorite. That unaltered igneous rocks are barren of the ordinary metals is indicated by the vast areas of those rocks that contain no lodes. The interior of granite masses are generally barren in all parts of the world. Scotland includes igneous rocks of all kinds and ages, and they have been exceptionally closely examined. Quartz-veins in them are innumerable; but lodes are scarce, and the most important in Scotland are not in the vicinity of great igneous intrusions; thus the lodes at Wanlockhead are in sediments and the few igneous rocks are older than the ores. Some of the most extensive areas of igneous rocks, such as the Deccan, Equatorial Africa, Iceland, the volcanic islands of the Atlantic, are practically free from lodes. Where, however, igneous rocks are traversed by deep-seated tension faults, as in the Rocky Mountains, they contain important ore-fields.

The distribution of ores in igneous rocks is usually independent of the nature of the rock. Different parts of one igneous rock may have different ores, as at the Butte copper field, Montana. Special rocks have, it is true, been regarded as attended by particular ores, such as norite by nickel; but various igneous rocks have been called norite apparently because nickel occurs with them. Granodiorite was regarded as the plutonic rock most intimately connected with gold, before it was realized that the granite of the petrographer is relatively scarce. Platinum is often found with serpentine; but only a most optimistic prospector would expect platinum wherever serpentine occurs, and as serpentine is an altered rock the platinum ore may have been formed during the secondary changes. Many ore-fields have no igneous rocks yet the gold-quartz of their lodes, as at Warrandyte in Victoria, may be indistinguishable from that of a lode beside a dyke. As ores of different kinds exist in one igneous rock, and ores of the same kind in different igneous rocks, the source of most ores is outside the rock in which they occur.

THE ORE-ZONE—The source of the ores appears to lie in a zone deeper than that of the ordinary igneous rocks (Gregory, "Ore Deposits and Distribution in Depth," *Tr. R.Inst.*, 1906, p. 9). The most certain fact about the interior of the earth is its high specific gravity which is probably due to its large proportion of metals. If the specific gravity of the earth increased evenly from the surface to the centre, the rise in specific gravity would be so slow that rock heavy with metal would not occur sufficiently near the surface to feed the lodes. But the innermost core of the earth (cf. p. 16) is probably lighter than the nickel-iron around it, and the barysphere is doubtless surrounded by an ore-zone composed of mixed silicates and metallic minerals (Fig. 8). The surface of the barysphere is probably irregular and peaks rise from it into the lithosphere and upraise the overlying ore-zone to a level at which they feed the lodes.

Magmatic water from the ore-zone rises through the overlying plutonic rocks and carries metals upward along fractures and fissures. Ore formation is naturally often associated with igneous intrusions, because they rise most readily in fractured areas, and as the intrusion of an igneous mass would rupture the adjacent crust. The predominance of lodes in the older rocks is natural, because these rocks are nearest the ore-zone and have had the longest time for impregnation from it. Ores occur in later igneous rocks where the ascent of materials has been rendered possible by increased gas pressure due to heat and the existence of channels due to fractures and fissures.

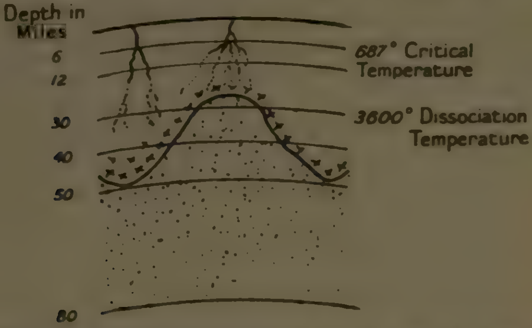

FIG. 8.—DIAGRAMMATIC SECTION OF THE EARTH'S CRUST.

Diagrammatic section of the earth's crust showing a rise of the barysphere (dotted) above its normal level of about 40 miles to less than 30 miles, whereby it carries the ore-zone (xxx) above the zone of the dissociation of water at the depth of 30 to 40 miles. The rising water-vapour converges into the main ascending currents and condenses to water on reaching the critical temperature of water at the depth of from 6-12 miles.

From the ore-zone there is an ascending sequence, successive metals being deposited as they come under suitable conditions of pressure and temperature. Gold ores are most abundant in the pre-Palæozoic rocks. Tin and tungsten generally occur in and near the plutonic rocks which are exposed in the roots of the upper Palæozoic or Altaid mountain system; they are not found in any quantity in connection with the Alpine-Himalayan movements. Copper which occurs above tin in the Cornish mines (Fig. 9), still requires a moderate temperature for its formation, as is shown by its frequent formation in a contact ore. Lead, silver, and zinc are found in still higher levels, and are often deposited in grits and limestone which show less alteration by heat and pressure than the rocks associated with most copper ores. Mercury, the characteristic ore of the younger mountain systems, is often found in small quantities in hot springs and their sinters, and its chief ore-fields are in bands intensely shattered by the Middle Kainozoic

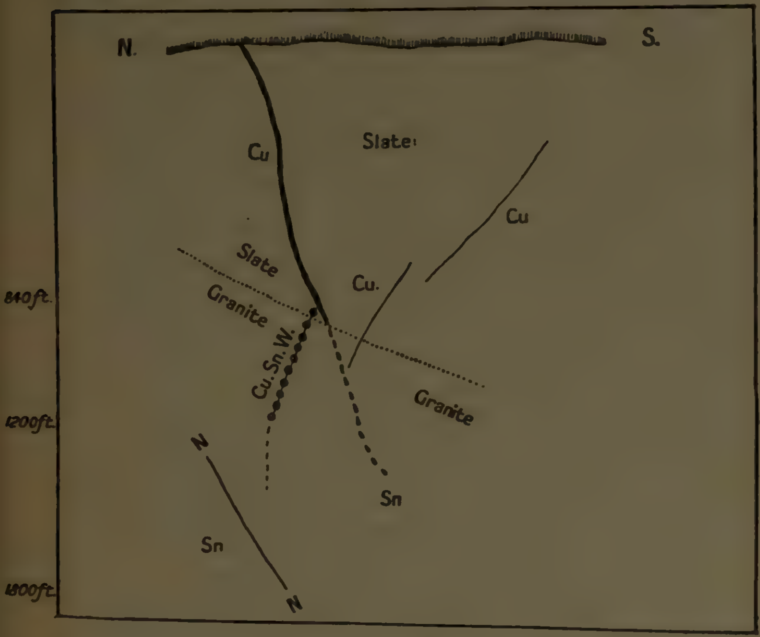

FIG. 9.—A COPPER TIN LODE.

The passage of copper lodes (Cu) in slate into deeper tin lodes (Sn) in granite. East Pool and Wheel Agar Mine, Cornwall. (After Collins.)

N, N, the north lode, Cu Sn W—north branch from the main lode containing ores of copper, tin, and tungsten.

mountain folding. The material of the ore-zone and barysphere may be regarded as igneous in the sense that they are holocrystalline and are formed of minerals that consolidated under high temperatures and pressures ; but metallic ores do not appear to be primary constituents of the ordinary igneous rocks of the earth's crust. Even the deepest seated plutonic rocks have received the metals in their lodes—except such as iron, manganese, and aluminium—from an underlying layer.

PLUTONIC, JUVENILE, AND MAGMATIC WATERS—The normal influence of igneous rocks in ore formation is indirect. Their intrusion produces fractures and fissures along which solutions can pass, and they raise the temperature so that the gas pressure forces the water upward. The main introduction of metals into the upper layers in the lithosphere, in addition to its normal constituents, is by the ascent of deep-seated water. This water is known as *plutonic* from its deep origin, or as *magmatic* after its derivation from igneous magmas, or as *juvenile* (Suess) since it is making its first appearance on the earth's surface.

A large quantity of this water is constantly arising from the interior (cf. Chap. XIX, pp. 220-2). It must begin its ascent through minute spaces. The liquid cavities in quartz often occur in lines passing from one crystal to the next, showing that the entrance of the liquid was after the consolidation of the quartz. This movement must be very slow. At depths of 6 to 12 miles the temperature is probably above 687° F., the critical point of water, which at it can exist only as steam. Below 30 or 40 miles, the temperature would be above 3600° F., and water would be dissociated into its constituent gases, which could combine only in a zone cooler than their dissociation point. Water after its formation would gradually work its way upward into a zone where fissures and cracks would enable it to ascend more freely. That fractures happen at great depths in the crust is shown by the evidence of earthquakes which result from deep-seated disruptions. Ruptured rock surfaces at great depths would remain in close contact, but not too close for the passage of films of superheated water. Ruptures must occur below the level where plutonic water begins its ascent in innumerable tiny trickles through thin spaces or scattered pores. This water being superheated would be a powerful solvent, and would thus obtain alkalis, that increase its power of dissolving quartz and metallic sulphides. The metallic barysphere, like the iron meteorites, doubtless contains sulphides, such as the iron sulphide, troilite, and phosphides (e.g. schreibersite), and carbon as graphite. The solution of troilite would give rise to ferrous sulphate, which is a solvent for gold. The water would also include chlorides, and fluoric and boric acids. This complex solvent would work its way upwards through the rocks, dissolving from them silica and metallic sulphides. The small spaces would unite into large channels along major fissures and fault planes, and through them solutions would rise more quickly. From the lower zone of solution the water would reach conditions under which it would begin deposition. It would be constantly passing under less pressure and lower temperature, and both influences would throw materials out of solution. Chemical reactions would aid, as contact with lime would neutralize acid solutions, while carbon by reducing the ferrous sulphate solution would precipitate metallic sulphides; and as gold would no longer be soluble it would be precipitated at the same time. Hence solutions rising up fissures, and especially up the great faults which mountain structures show to extend over 100 miles deep, would bring to the surface metals from the ore-zone.

MAGMATIC ORES—The nature of these solutions is the main current problem in ore genesis. As the solvent must be mostly water and the temperature high, they are justly called hydrothermal; but as many authorities held that all the water on or in the earth's crust falls upon it as rain, the ore-forming solutions were attributed to surface water which had sunk underground, had there dissolved scattered metallic particles and deposited them in lodes as the water was forced to the surface by the gas pressure due to heat. Ores formed by this process of lateral secretion appear to be more abundant than has been generally admitted in recent years; they include not only ores of iron and manganese, but many others, such as the copper ores of Mansfeld, of Cheshire, and some of those of Katanga, some of the lead and zinc ores of Mississippi and the rich gold ores of Mount Morgan.

For ordinary lodes the lateral secretion theory has been superseded, and the ores are attributed to water given off from the interior of the earth. This water is generally described as magmatic, but that term is ambiguous and is used for ore deposits with three different meanings. Harker (*Nat. Hist. Igneous Rocks*, 1909, p. 31) defines a magma as "molten rock material." "The original molten rock matter is conveniently termed magma," says Tyrrell (*Principles Petrol.*, 1926, p. 46); Lindgren (*Tr. Amer. I.M.E.*, lxxiv, 1927, p. 77) gives a definition in the language of physical chemistry which means the same, as he remarks (*ibid.*, p. 76), magma is "the material from which all our igneous rocks have consolidated." In accordance with this petrographic use of the term many ores are described as magmatic, being attributed to the direct consolidation of molten rock material. R. H. Rastall (*Geol. Met. Dep.*, 1923, p. 109) entitles one group of ores "magmatic segregations; ores actually separated from igneous magmas by crystallization;" and W. Lindgren devotes a chapter (*Min Dep.*, 1913, pp. 735-72) to "Mineral Deposits formed by Concentration in Molten Magmas." The magnetites of Taberg, of Lapland, and the Adirondacks (cf. p. 140), the nickel ores of Sudbury and South Africa (cf. pp. 114-19), and the tin of South Africa (Recknagel. *Tr. G. Soc. S. Afr.*, xii, 1910, p. 128), have been represented as magmatic in this sense of the term; but in the account of the ores in the following chapters it is claimed that the ores thus formed are few and of little present commercial importance.[1]

The second set of ores called magmatic are due to water of magmatic origin. This use of the term was begun by J. H. L. Vogt (*Z. prakt. G.*, 1894, p. 381), who extended it to emanations that are given off after the consolidation of the molten material and are discharged through hot springs, fumaroles, and solfataras. Many authors have followed Vogt's lead and accepted as magmatic all ores due to water of magmatic origin; thus W. H. Goodchild (*Ming. Mag.*, 1918, xviii and xix) includes even the Banket of the Rand, and truly says "they are ores of endless variety" (*ibid.*, xviii, p. 135). According to this usage many beds of tufa,

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[1] Cf. Gregory, "Magmatic Ores," *Tr. Faraday Soc.*, xx, 1925, pp. 449-58.

sinter, and chert are magmatic; the term covers both igneous and aqueous products, and is too comprehensive to be of practical value.

A third use of the term magmatic is that of J. E. Spurr who in his "Ore Magmas" (1923, restated in *Tr. Amer. I.M.E.*, lxxiv, 1927, pp. 99-115) adopts an intermediate position; he excludes ores due to magmatic waters, and regards a large variety of lodes as due to the intrusion of "highly concentrated and dense magmatic residues" allied to pegmatites. He states that "a magma is a solution" (1923, p. 73). His ore-magmas include magmatic waters in which the material dissolved is highly concentrated. The material ruptures the rocks and as "veindikes" fills the fissures it has made. These magmas behave like cement which, when injected into a foundation, forces its way into rocks in thin sheets like a dyke.

This view of gold-quartz veins was adopted by T. Belt (*Mineral Veins*, 1861) for those of Victoria; and being interested in his memoir I examined many Victorian quartz-lodes in reference to their origin as igneous intrusions; but the lodes seemed due to solutions, which, though hot, were cooler than even pegmatites, and which rose through fissures and in places replaced the walls; this replacement is shown by the passage from pure quartz to the country through a silicified zone, and by the included masses of rock being in their original place and having been enclosed by the growth of quartz around them. The walls have been altered by impregnation by solution and not baked by a molten intrusion; and the tongues in the adjacent rocks present the aspect of filled cracks and aqueous replacements. Spurr compares his "veindikes" to pegmatites, which occur galore in countries such as Scotland and Kenya Colony, where ore deposits are deplorably scanty; pegmatites are associated with such useful mineral as mica, apatite, kaolinite, and the gems and sparse metallic minerals as of tin occur in them; but pegmatite seldom contains workable metallic ore.

The distinction between molten rock material, magmatic waters, and Spurr's *Ore Magmas* is not easy to define, because there is no absolute division between molten and dissolved materials. For practical purposes, however, a solution is liquid through the action of a pre-existing solvent; a molten material is liquid owing to high temperature. The problem is therefore whether the ore-forming solutions are given off from some deep layer within the earth as water vapour, which, after its condensation, dissolves metallic constituents from the ore-zone; or whether ore solutions are given off by the molten rock as a dense fluid composed of silicates and silica, and containing water and volatile constituents.

Whether the ore-forming solution began as water or as residual molten matter squeezed out of the consolidating igneous rock is necessarily uncertain. The decision depends on the general balance of evidence given by the primary deep-seated ores; and the author feels that the ores due to hydrothermal action are more abundant and important than those formed as intrusive dykes of molten magma.

Igneous ores were defined by Kemp as "excessively basic development of fused and cooling magmas" (*Ore Deposits U.S.*, 1900, p. 59), but such ores are few and, except for chromite, are commercially unimportant. The aqueous ores include all deposits from ordinary solutions (exclusive, i.e. of solid solutions and molten magmas), and as most of these ores are due to the cooling of hot solutions, they are mainly hydrothermal.

LODE DEPOSITION—HYDATOGENESIS, PROPYLITIZATION, AND PNEUMATOLYSIS—The chief metallic lodes are deposited along great fault fissures; and the materials depend primarily on the solutions that flow through the fissures. The simplest process (*pneumato-hydrolysis* or *hydatogenesis*) is the action of superheated water, which attacks the felspars, removes alkalis and lime, and re-deposits the other constituents as grains of quartz, with often some secondary felspar and such minerals as zoisite. The pyroxenes and amphiboles are broken up into granular mixtures of epidote, zoisite, and chlorite. The resultant rock under microscopic examination is a fine-grained granular mosaic in which no trace of the original structure is left; but the outlines of the original crystals and the structure of the rock may often be recognized in hand specimens and in examination under the microscope in ordinary light. Igneous rocks thus changed have an unusual lustre and were described by von Richthofen as propylite; the change was explained by Judd (*Q.J.G.S.*, xlvi, 1890, p. 366), from study of the rocks in Mull, as due to solfataric action, and it is known as *propylitization*. The superheated water may not be pure; it may contain iron sulphate and gold which is deposited in the altered portion of the igneous rock, as for example, in the propylitized porphyrites around Wood's Point and at Walhalla in Victoria. A second process *pneumatolysis*, is due to the action of superheated water or steam associated with boric and fluoric acids, or sometimes phosphoric acid. In this case the change is more intense; the felspars are altered to kaolinite (china-clay), topaz; and tourmaline; and tin, brought up as vapour of stannic chloride or stannic fluoride is deposited as tin oxide, cassiterite. This process produces tin ore and others, and also mica, phosphate, and pegmatite.

A third type of deposition is by alkaline solutions which dissolve silica and metallic sulphides, and re-deposit them, with quartz as the common veinstone, as the solutions cool at higher levels. This process has formed most of the primary lodes, and in them the metals are usually present as sulphides.

A fourth kind of deposition is by chloride solutions, which at the Nevada Hot Springs carry iron, arsenic, antimony, and mercury. These metals may be deposited as sulphides or oxides. Small veins of hæmatite are formed around volcanic steam vents by the decomposition of iron chloride by steam.

LODE STRUCTURE AND DEPTH OF ORE FORMATION—The structure of lodes depends upon the spaces in which they are formed. As solutions rising through fissures are cooled on approaching the surface they deposit material as successive layers or crusts on each wall of the fissure (cf. p. 11). The nature of the layers varies during the formation of the vein. The temperature and composition of the water probably varies spasmodically, with renewed earth-movements or intrusions, and these changes affect the layers of these crustified lodes (Posepny. *Tr. Amer. I.M.E.*, xxiii, 1894, p. 207). In most lodes the metallic ores are derived from below; the veinstones may be largely contributed from the rocks on the sides, as water percolating through them brings with it silica, carbonate of lime, and barium oxide derived from felspar, and they are deposited as quartz, calcite, and barite ($BaSO_4$).

The ore-forming solution may enter the rocks beside the fissures and deposit its constituents as an impregnation. The lode passes gradually into the country through a band impregnated with metallic minerals, such as the "capel" beside the Cornish tin-lodes, the "emborroscado" beside the pyrite masses in Spain, and the irregular network of veinlets forming a *stockwork*. Still further impregnation replaces the country rock entirely by a *replacement* or *metasomatic ore*. Such an ore-lode may fade outward into the country, as in some Rhodesian mines, where ore rich in gold with no trace of the original rock constituents passes through ore in which the felspars can still be recognized, into country with only a slight impregnation of metallic minerals. One extreme development of replacement deposits produces the great pyritic lenticles (cf. Chap. VI) which may be hundreds of feet across, and yet include no fragment of the unaltered country as large as a walnut, though the structure of the original rock may be recognizable by the sheen on a surface of pyrites.

It has been considered that ore formation is possible only within a shallow zone, as no spaces can exist where the rocks flow under the pressure. The depth of this zone is being steadily increased from Heim's estimate in 1878 of 1½ miles, and Van Hise's of 7·4 miles, to Sir Charles Parson's (*Nature*, 20th October, 1904), of at least 12 miles. His view was confirmed by the experiments of F. D. Adams (*Journ. Geol.*, xx, 1912, pp. 115, 117) who proved that empty cavities persist in granite under the pressure of 11 miles deep, and that cavities filled with water or gas would remain at a still greater depth. Ore formation by the filling of cavities may therefore take place to the depth of at least 12 miles and by replacement to indefinitely greater depths.

ORE SEQUENCE IN DEPTH -Crustified deposits often show a succession of different ores and veinstones in a transverse section of the lode. An analogous vertical succession also occurs owing to zonal variation controlled by temperature. Some lodes have been formed at high temperatures near the source of the ores and plutonic water; others have been formed under cooler conditions near the surface. No known lode includes the full vertical succession of ores. At great depths the change in temperature and pressure is very gradual; in lodes formed under such conditions the ore deposits may be similar through a vertical range of 6000 feet as in the mines of Mysore, or of 4000 feet in the saddle-lodes of Bendigo. The full succession in depth is determined by the correlation of lodes in different mining fields. The heavy metals are naturally often associated with deep-seated plutonic rocks such as platinum with basic and gold with acid varieties. The great depth at which many gold lodes were formed is indicated by their vertical uniformity, although there is usually a fall in the quantity of gold but improvement in its quality as the lodes are followed downward. Primary tin ore is restricted to deep-seated high temperature deposits. Some Cornish copper mines by deeper working become tin mines, as ores of tin occur below those of copper.

Copper lodes often reach the surface, but in some cases, as in Cornwall and notably at Butte (cf. p. 91), the lodes at the surface contained no copper but silver, lead, and zinc. These three metals are usually intimately associated in ores; lead is often most abundant in the upper part of a lode, while zinc increases below where the temperature was higher.

Gold and silver ores have a great vertical range, having been deposited in plutonic rocks at great depths, and also near the surface. A general ascending sequence passing through tin, tungsten, copper, zinc, lead, iron, and manganese, has been established,[1] but it is not universal, and is in places reversed. As the sequence depends upon the temperature of the rising solutions, variations are only natural; for the intrusion of igneous rocks is probably slow, with many pauses during which the overlying temperature would fall. A fresh advance of the intrusive mass would cause the high temperature minerals to invade the zone where those formed at lower temperatures had already been deposited. The sequence would be expected to show variations comparable to those in the successive layers of a crustified lode.

The metallic constituents of a lode are not as a rule uniformly deposited along it, but are collected in rich bands or

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[1] E.g. E. H. Davidson, *Geol. Mag.*, lviii, 1921, pp. 505-12; R. H. Rastall, *Econ. Geol.*, xviii, 1923, p. 109; H. Dewey, *Proc. Geol. Assoc.*, xxxvi, 1925, pp. 107-35. The sequence of the veinstones is described by H. B. Cronshaw, *Tr. I.M.M.*, xxx, 1921, p. 411.

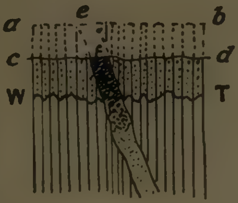
patches. The most characteristic concentrations are "ore shoots," which are often irregularly funnel-shaped or cylindrical bodies of ore. Such shoots may be due to concentrated precipitation of the metallic constituents of a solution by reactions with the wall rock of the lode, or with a solution that enters the lode fissure from some side channel. A shoot may be formed where a metalliferous spring enters a sheet of water in a fissure. Some masses of iron ore have been formed as igneous segregations, such as that at Taberg in Sweden. Iron ore bodies of greater commercial value have been formed as concentrations by the descent of surface waters, which dissolve iron from some iron-bearing rock and carries it down until it is stopped by impermeable material and is precipitated in mass. Thus have been formed the rich masses of kidney iron ore of the north-west of England (cf. p. 135) and the colossal bodies of iron ore beside Lake Superior. Some funnel-shaped bodies of lead ores, which are often stalactitic, are due to the concentration of scattered particles of lead by descending solutions.

Efflorescent Minerals—Exceptionally rich mineral concentrations are formed near the surface as ascending water there undergoes rapid chemical and physical changes. The water may evaporate and deposit its mineral matter as a bed of tufa or sinter around a spring, or as a widespread efflorescent layer or crust. In a dry climate very soluble salts may be thus deposited, such as the nitrate of soda of Chile and Peru; in a climate with alternate wet and dry seasons limestone and chert may be deposited by the water which has soaked into the ground during the rains, being sucked to the surface and evaporated during the dry weather. Efflorescent limestones may form a nodular sheet, such as that which mantles the undulating surface of the Mallee country in north-western Victoria, the Kankar of India, and the caliche of Mexico. The Mallee limestone is interbedded with chert and ironstone where the descending rain-water dissolved silica or iron. Amongst the important minerals formed by the alternate descent of rain-water during the wet season, and evaporation from the surface during the dry season are bauxite, the chief ore of aluminium (p. 153) and laterite.

Superficial ores are formed on the floors of lakes and in swamps by the reduction of metallic salts by decomposing organic matter or bacteria; thus are formed the bog-iron ores which are periodically dredged in Swedish lakes, and numerous beds of iron ore formed in swamps, such as that at the Mesa de los Pinos at Rio Tinto. The *gossans* or "iron hats" that cover most lodes are also due to the superficial formation of iron oxide. The iron pyrites in a lode is oxidized by descending rain-water and is removed in solution leaving the quartz full of cavities or, as the miners describe it, as mouse-eaten; the insoluble veinstones are stained brown by the iron oxide formed from the pyrites. Some of the minerals leached out of the gossan may be carried down along the lode (Fig. 10), and on reaching water-level may be re-precipitated as iron sulphide with metallic gold, or as copper sulphide, such as chalcocite, or pockets of silver-lead ore; thus have been formed those secondary enrichments, which have yielded many of the richest prizes in mining history.

FIG. 10.—DIAGRAM ILLUSTRATING SECONDARY ENRICHMENT.

Diagram illustrating secondary enrichment; *ab*, former surface of the country, which, with the top of the lode, *ef*, has been removed by denudation. Below the present surface, *cd*, the rocks have been decomposed to the depth of the water-table, WT. The upper part of the lode has been altered to a gossan with concentrated rich ore. Below the water-table is a further secondary enrichment, below which the lode continues with primary low-grade ore.



BEDDED MINERAL DEPOSITS—The complete evaporation of lakes and lagoons may give rise to thick widespread beds of salts. The largest of them are formed by the evaporation of arms of the sea, in which the salts are precipitated in order of their insolubility—gypsum, rock salt, and potassium and magnesium chlorides, which remain in solution till the last of the bittern (p. 206) has evaporated. Beds of salt are also formed by the evaporation of lakes; the kind of salt depends upon the composition of the adjacent rocks; thus potash salts are deposited where the rocks contain much potash felspar.

Mineral sheets or seams may also be formed by plants and animals which grow on the earth's surface or in shallow waters and lagoons. The most important of the organically formed minerals is the coal series, ranging from peat through lignite and bituminous coal to anthracite and graphite, and through cannel coal to oil shale. The asphaltic limestones owe their special value to their organic constituents, which when heated form bitumen. The phosphatic rocks are also usually of organic origin, their phosphoric acid being obtained from bird dung deposited on islets, or bones carried into lagoons. The phosphoric acid is carried into the underlying material and converts it into phosphates, of which the phosphate of lime is one of the most valuable fertilizers.

ALLUVIAL ORES AND PLACERS—Surface conditions also give rise to those sedimentary ores in which the useful constituent has been obtained from an older mineral deposit, which has been broken up and its grains left in beds of sand or gravel forming alluvial ores or placers. The term placer is a Spanish word used for a sand-bank and for pearl fisheries. The most important of these mechanically-formed ores are those of heavy metals which are insoluble in surface waters under ordinary conditions. The chief placer deposits contain gold, platinum, tin, and the gems. Most placers are due to rivers, which deposit ore washed out of lodes along their course. Deeply buried river beds are known as "deep leads." Marine placers are formed where the surf breaks up metalliferous rocks and deposits the metallic grains in patches, as at Nome in Alaska and in New Zealand. The most important marine placer is that ancient gold-bearing shingle, the Banket of the Rand, which has proved the most prolific of the world's gold ores.

MICROSCOPIC STUDY OF ORES—Knowledge of the deposition of ores and help in their classification has been greatly advanced by their microscopic examination. The study of rocks was revolutionized by Sorby's method of cutting transparent sections for microscopic study, and the same process applied to ores has often replaced speculation by direct evidence. The microscopic study of ores is hindered by the opacity of many of the species, but opaque minerals are examined in polished surfaces (for the method, see R. W. Van der Veen, *Mineragraphy*, The Hague, 1925). Microscopic study shows the conditions under which the ore was formed, the order in which the different constituents were deposited; and which of them are primary and which are secondary. It also shows which of the minerals in an ore were deposited by the agent that introduced the metals, and whether the minerals are still as they were originally deposited or whether they have been redeposited by descending surface waters. It also reveals in replacement ores, by the shadow of the original structure, what material the ore has replaced; it may show, for example, that a phosphate of lime was originally a trachyte (as at Clipperton Island); that a gold-bearing quartzite was originally a dolomite or a fossiliferous limestone; that an ironstone has been formed by the alteration of a shelly limestone into a carbonate or oxide of iron. Many theories have proved untenable when microscopic study has shown that supposed sedimentary rocks were igneous, or that intrusive rocks were volcanic ash, and that a mineral that was thought to have been the first constituent to solidify in a molten magma was introduced long after the solidification of the rock.

CHIEF MINERAL DEPOSITS DUE TO SEGREGATION—Most of the minerals of special use to man consist of material that was widely scattered through the primeval matter of the earth. They have been concentrated by that beneficent process of segregation which draws like to like. The process is sometimes due to chemical affinity, and sometimes to the properties which cause mechanical concentration by wind and water. The primary mineral deposits are mainly due to ascending currents rising from the vast store of metals in the interior of the earth. Some rich secondary deposits are made upon or near the surface by the solution of scattered material by descending rain-water, and its deposition in concentrated form. Some superficial deposits are due to the mechanical separation of ore from dross by Nature's use of the methods adopted in ore-concentrating machinery. Other beds of mineral matter, such as coal and limestone, are due to the gregarious habits of plants and animals; they live in forests or jungles or in colonies, and leave their tissues, shells or skeletons in continuous sheets which are subsequently compressed and cemented. Varied processes of concentration have formed all those mineral segregations by the use of which man has gained his control over nature, and developed modern civilization.

PART II

ORE DEPOSITS

CHAPTER III

ORES OF GOLD

Gold and its Qualities—Gold (at. wt., 197·2; sp. gr. 19·3; melting-point, 1950° F.; standard price, 84s. 11½d. per oz.) is the most precious of the widely-used metals, and owes its influence on history and industry to its beauty, scarcity, and to the high malleability which renders it easy to work. As it does not combine with oxygen it does not tarnish or rust, and it can be used for decoration in extremely thin films as gold leaf. Its heaviness makes it convenient for coins. It must have been one of the first metals used by man, for its grains are widely distributed, conspicuous, and easily wrought into ornaments.

Gold in Sea-water—Gold occurs in nearly every country which contains old rocks, and as it is claimed to be a universal constituent of sea-water, in which it would occur as a double chloride, it should be precipitated by light and organic matter into most marine deposits. The view that gold and silver are normal constituents of sea-water was based upon their presence in Muntz metal which had been used as sheathing of a brig, the Nina, after three years' cruise in the Pacific (*Proc. R. Soc.*, viii, 1857, p. 294); the gold and silver were attributed—except for the slight amounts in the original metal—to electrolytic deposition from sea-water. This possibility was supported by Sonstedt's claim in 1872 to have detected gold in the Irish Sea. The weightiest evidence for the general existence of gold in the water of the oceans is that of Liversidge. Doubts have often been thrown upon it (e.g. K. E. Andrée, *Geol. Meeresbodens*, ii, 1920, p. 582). Such gold as there may be in sea-water is probably secondary and does not explain the source of gold in lodes.

Gold Lodes and Igneous Rocks—Most of the chief goldfields of the world have been found by their alluvial deposits, in which the gold is conspicuous owing to its bright colour and the beating of small grains into large flakes. Primary gold is generally found in quartz-veins in the older rocks, though younger lodes are found in areas of great earth-movements and volcanic activity. The gold-quartz veins were at first regarded as igneous, owing to their frequent association with igneous rocks and their resemblance to dykes by their branching and cutting across bedding planes. Some quartz-veins contain felspar and have been regarded as pegmatites in which nearly all the felspar has been deposited in some lower position, leaving only molten quartz to solidify at the upper end of the intrusion. Secondary felspars, however, occur in limestones, and the absence of the typical igneous minerals from the quartz-veins and of contact metamorphism along the edges and the fact that the quartz in the lodes is the low temperature variety (i.e. β-quartz), show that the veins were formed under aqueous conditions at a moderate temperature, and were introduced in solution and not as a molten intrusion.

The vein-quartz often passes indefinitely into the country rock. The white quartz passes gradually into dark quartz, and through silicified into normal slate. In quartz-veins in granodiorite all stages can be seen between silicified fragments of that rock and pure quartz. Quartz-veins often include fragments of the country rock that have resisted silicification; and as such blocks are often in their original position the quartz around them grew by replacement.

Most primary gold-quartz lodes are due to deep-seated hydrothermal action. Pneumatolytic conditions are in places shown by axinite, tourmaline, and kaolinite. The deep-seated origin of some lode gold is indicated by its association with tellurides, as at Kalgoorlie and Cripple Creek. In other cases the action was propylitic, for superheated steam and carbonic acid altered the felspars into a mosaic of secondary quartz and felspar, and the ferromagnesian minerals into chlorite, epidote, and zoisite.

The propylitic origin of some gold explains the controversy as to whether dykes enrich or impoverish adjacent lodes. A lode may be poor where in contact with a dyke and rich where separated from it, and *vice versa*. Such apparent inconsistencies are explained by the A1 Mine at Wood's Point in Victoria; it consists of horizontal floors of quartz in hornblende-porphyrite; where that rock is normal the quartz is barren, but where the rock has been altered to propylite the quartz-floors are auriferous. The gold is due to the propylitization and not to the dyke.

THE CLASSIFICATION OF GOLD ORES

Gold, owing to its ubiquitous distribution is found in a great variety of ore deposits. Excluding some of the less important occurrences in contact deposits, and as an accessory constituent in many sulphides the chief ores may be classified as follows:—

Sect. A—*Primary*—

- I. *Gold-quartz Fissure Lodes*—
  - (*a*) In sedimentary rocks. California; Ballarat.
  - (*b*) In gneisses and schists. Mysore; Brazil; S. Rhodesia.
  - (*c*) In volcanic rocks. Rocky Mountains; New Zealand.
  - (*d*) Pneumatolytic. Cripple Creek; Passagem, Brazil.
- II. *Isolated Gold-quartz Veins; Saddle and Ladder Lodes*—
  - (*a*) Saddle-lodes. Bendigo; Nova Scotia.
  - (*b*) Ladder-lodes. Wood's Point; Little Bendigo, Victoria; Berezovsk.
  - (*c*) Radial-lodes. Charters Towers.
- III. Impregnations and Replacement Bodies. Homestake, N. Dakota; Alaska Treadwell; Kalgoorlie, W. Australia; Porcupine, Ontario.

Sect. B—Secondary enrichments. Londonderry, W. Australia; Mt. Morgan, Queensland.

Sect. C—*Alluvial Deposits*—

- Surface drifts and leads.
- Deep leads. Victoria and Kanowna.
- Marine placers.
- Ancient placers. Rand Banket; Gold Coast; S. Dakota; Morro Velho, Brazil.

SECTION A. PRIMARY ORES

I. GOLD-QUARTZ FISSURE LODES—CALIFORNIA, BALLARAT, MYSORE—The character of these lodes varies so greatly with the nature of the rock fissures that they fall into four divisions, those in older sedimentary rocks, in pre-Palæozoic gneisses and schists, in the younger volcanic rocks, and pneumatolytic lodes.

The standard gold-quartz lodes are those in the Sierra Nevada of California. The Sierra Nevada consists of pre-Palæozoic schists and gneiss, covered by slates, sandstones, and igneous rocks, which range in age from early Palæozoic to Lower Cretaceous. At the end of the Jurassic or beginning of the Cretaceous the country was invaded by massifs of granodiorite with offshoots of augite-porphyrite, diabase, and serpentine, and was uplifted by faults, beside which quartz was deposited in fissures and fractures and by replacement of slate and limestone. Gold and gold-bearing pyrites were deposited in the quartz. The date of their introduction is shown by the placer gold in some conglomerates, which are at latest early Cretaceous. The quartz-veins form a series of belts, which extend 700 miles in length by from 20 to 60 miles in width. The greatest of these belts is "the Mother Lode of California," which trends N.W. for 112 miles through Mariposa, Calaveras, and Eldorado, localities famous from the writings of Bret Harte. The "Mother Lode" is a mineralized belt with innumerable irregular discontinuous veins, generally in slates near granodiorite, and sometimes along the contact; but they also occur in the granodiorite or at considerable distances from it, or in serpentine. The distribution of the gold is irregular; of two parallel adjacent veins one may be barren and the other rich. Pure white or "buck-quartz" is generally barren. Quartz banded with thin lines of micas, such as mariposite (a potash-mica coloured by chromite), and roscoelite (a mica with 25 per cent. of vanadium oxide) is usually richer. The other common veinstones are calcite and dolomite, and, in places, barite. The metallic minerals are sulphides, chiefly pyrites, with a little galena and blende. The gold usually occurs free in pyrites.

The mines have been worked to depths of about 4000 feet;

and as the deeper ore is poorer, in 1923 only 7 lode mines were at work.

The Ballarat Goldfield is another historic field.[1] The discovery of its rich alluvial deposits in 1851 established the mining fortune of Australia and led to the great influx of population. The field consists of Lower Palæozoic slates and quartzites, with felsite dykes derived from granite that outcrops 2 miles to the east. At Ballarat West the lodes are continuous quartz-veins, that vary in width from 2-10 feet, and expand into replacement bodies 100 feet thick. The gold occurs in irregular shoots which have been worked to the depth of 1300 feet; the gold yield decreased downwards though in places the copper, galena, and blende increased.

In the goldfield of Ballarat East the quartz-veins form an irregular branching and intersecting network. Most of the quartz is barren, but along the veins are rich irregularly branching patches of gold. These "nuggety patches" have given rise to the nuggets (a term probably based on ingot) which were found in the local gravels. Nuggets are usually rounded masses of gold, some of which are free of quartz and have a concentric structure. The Welcome Stranger Nugget, found at Moliagul in N.W. Victoria, contained £10,000 worth of gold. The belief is persistent among miners that the nuggets grow in the gravels, as none have been found in lodes, and as the gold in nuggets is "finer" (i.e. purer) than that in the adjacent lodes. Support to this view was given by an experiment that suggested that gold dissolved in water circulating through the deposits would be precipitated on free gold, which would grow into nuggets, as flints grow in chalk. The existence of gold in the water of alluvial deposits in British Guiana has been proved by Sir J. B. Harrison. It has also been found in the rotting vegetation of many placers; but this gold has probably been carried there mechanically, just as in the "moss-mining" of California the gold in the ash of moss collected from the rivers was probably filtered from the water and not precipitated from it. Alluvial gold is finer than it was when in a lode, as silver, being more soluble, is removed by prolonged

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[1] W. Baragwanath, *Mem. G.S. Victoria*, xiv, 1923; J. W. Gregory, *ibid.*, iv, 1907.

washing in water. The conclusive evidence against the growth of nuggets in the gravels is their distribution. No nuggets are found in goldfields where the gold in the lodes is in minute particles; or they may be found, e.g. in the Rand in South Africa, only where coarse gold has been formed in secondary quartz-veins. In Ballarat East, as shown in Fig. 11, the nuggets were found along a line where nuggety patches occur in the lodes. These patches are exposed on the hillside; pebbles washed down the slope, knocked out the brittle quartz and hammered the patch into a nugget. This origin is consistent with the investigations on nuggets of A. Liversidge (*J.R. Soc. New South Wales*, xxvii, 1893, p. 343; xl, 1906, p. 161).

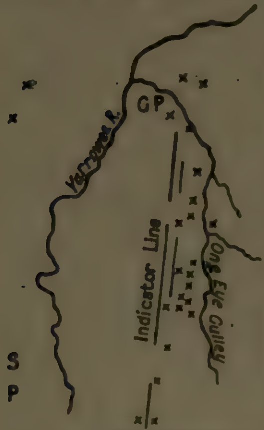

Fig. 11.—Distribution of Gold Nuggets.

Distribution of gold nuggets, *x*, at Ballarat, showing their relation to the Indicator line. The gold nuggets in the north-western corner may be due to another "Indicator." GP, Golden Point; SP, Sebastopol Plateau.

The mining of Ballarat East was dependent on some clue to the arrangement of these nuggety patches. One having been found where a quartz-vein met a vertical brown line, this line was followed and led to other patches of gold, where it met a quartz-vein. The line was therefore called the indicator. Several of these indicators have been found in the slates at Ballarat East, and have been traced for eight miles along the field. They vary from about one-sixteenth to a quarter of an inch in thickness; the main indicator sometimes divides into three layers which have a total thickness of half an inch. Their thickness and their dark colour, below the oxidized zone, is expressed by the names of the Pencil Mark and the Telegraph Line given to two of them. The microscopic structure of the indicators shows that most of them consist of bands of chlorite developed in the slate along planes of slipping (Fig. 12). The indicators in places occur along the cleavage planes, but often cross them. An indicator may consist of a band of tiny lenticles each along a cleavage plane. The deposition of the gold in the quartz opposite the indicator is probably due to the reduction of the gold solutions by the oxidation of the ferrous iron in the chlorite. The miner follows the indicators and extracts the quartz which intersects them.

The Ballarat East Mines are nearer the granite than those of Ballarat West, and their deeper origin is indicated by the more frequent occurrence of albite-felspar in the quartz. The Ballarat West lodes may subdivide below into irregular veins like those of the eastern field.

FIG. 12.—SECTION ACROSS AN INDICATOR.

Section across an Indicator at the New Normanby Mine, Ballarat East, magnified 30 diameter. The indicator is transverse to the bedding; it consists of lenticles of chlorite which have developed along the bedding planes.

Gold ores are especially characteristic of the pre-Palæozoic crystalline rocks which yield gold in many countries, and include in South and West Africa, India, Siberia, Australia, and North America, some of the most productive goldfields of the world.

The Mysore Goldfield in Southern India (T. Pryor, *Tr. I.M.M.*, xxxiii, 1924, pp. 95-115) consists of pre-Palæozoic rocks, of which the foundation is mainly hornblende-schist. It has been invaded by masses of granite and gneiss, and by dykes of felsite. While these rocks were cooling the schists were fractured, and the fissures filled by dark, bluish-gray quartz-veins, which were widened by the replacement of the walls, residues of which remain as actinolite, pyroxene, and brown mica. After the igneous rocks had become quite solid, N.N.W. faults broke through the quartz-veins, and solutions from below introduced gold, pyrites, arsenopyrite, blende, galena, and chalcopyrite. That these solutions were pneumatolytic is shown by the abundant tourmaline, and some scheelite. The gold was deposited in rich shoots where it entered the inclined quartz-veins. Subsequently the country was broken by faults trending from N. to S. and they were filled with further lodes containing little gold, but tellurides and blende. The average gold contains about 1 per cent. of silver, and becomes finer with increasing depth owing to the greater solubility of silver. The Champion Lode is in places 40 feet thick but it narrows to a mere lode-track. It was worked in prehistoric times and has been mined to the depth of 6000 feet. The lode-quartz, when released from pressure in the mine workings, is apt to fly to pieces in fatal explosions or "rock-blasts."

VOLCANIC FIELDS—ROCKY MOUNTAINS AND NEW ZEALAND—In many volcanic areas gold-quartz veins occur along intersecting fractures due to earth-movements or to the shrinkage of the rocks. Typical examples occur in the Rocky Mountains of Colorado and the adjacent States. These mountains consist of Palæozoic, Jurassic, and Cretaceous rocks, in places covered by Eocene conglomerates. After deposition of the conglomerate volcanic eruptions discharged a volcanic breccia and vast lava flows of andesite and rhyolite. The volcanic areas were afterwards faulted and gold lodes deposited along the faults. Thus the Smuggler Vein of the Telluride Goldfield is a fissure vein which runs for many miles N. and S. and has been worked to the depth of 3500 feet; it consists mainly of quartz, with rhodocroisite ($MnCO_3$), calcite, siderite, and barite. It is cut across by the Revenue Vein, a lead-silver lode, and both of them are cut by the Pandora Vein of gold-quartz along a fault that throws the southern part of the Smuggler Vein to the E.

In the Camp Bird Field in Ouray County, Colorado, the volcanic breccia is traversed by a five-mile-long fissure vein,[1] which intersects numerous earlier lead-zinc lodes and contains shoots of pyritic gold-quartz ore that extend along the lode for over 1000 feet, and are about 500 feet high; they appear to have been fed by pipes of ore that go 800 feet deeper. The gold ore encloses fragments of the older lead-zinc ores; it shows no crustification, and appears to have formed by a single filling of the fissure.

The lodes in the volcanic areas are not themselves volcanic, and are more recent than the eruptions. The ores were deposited by solutions rising along fractures due to the

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[1] For latest account of the lode, cf. Spurr, who calls it a compound veindike, *Econ. Geol.*, xx, 1925, pp. 114-52.

settlement of the country after the volcanic activity. The ores are Middle or Upper Kainozoic in date, and have not the secondary enrichments common in older lodes.

New Zealand, in addition to gold-quartz veins in slates, has two goldfields in volcanic rocks with fracturing of a different pattern from that usual in the plateau eruptions of the Rocky Mountains; it is however similar to that at Gold Field, Nevada, which as shown by F. L. Ransome (*U.S.G.S.*, *Prof. Pap.*, 66, 1919, p. 196) was torn across by intersecting fissures without fault movements. In the Hauraki Goldfield in the North Island Kainozoic andesites and dacites were traversed by a network of ruptures along which were deposited quartz, calcite, pyrite, chalcopyrite, blende, galena, and gold. When the fissures were full the solutions were forced into the country and formed replacement lodes 50 feet, and at the 800 feet level, even 100 feet wide. Owing to the saturation of the country by the solutions the ore-shoots were remarkably persistent to the depths of 1000 feet, and they have been worked to the depth of 1900 feet (cf. J. M. Bell, *Tr. Austr. I.M.E.*, 1911, pp. 548-79; and P. C. Morgan, *Bull. Geol. Surv. N.Z.*, 1924, No. 26). The Thames Goldfield, on a peninsula E. of the Hauraki Gulf, illustrates the formation of a goldfield where the fracturing and ore deposits are shallower. The andesites there have been intensely altered hydrothermally to the depth of 500 feet, and traversed by veins of quartz with rich pockets of ore where the main veins are joined by small quartz stringers.

PNEUMATOLYTIC ORES—CRIPPLE CREEK, AND PASSAGEM, BRAZIL—Cripple Creek, in the red pre-Cambrian granite of Pike's Peak, Colorado, represents the pneumatolytic goldfields. It is in the pipe of a Middle Kainozoic volcano and pneumatolytic agents are shown by the characteristic mineral being telluride of gold, by the abundance of fluorite, and the alteration of felspars into kaolinite (cf. p. 169). The volcanic breccia in the pipe has been so silicified that its original nature is recognizable only under the microscope. The breccia was cut by dykes of basalt, andesite, and phonolite, and has been torn by fractures due to shrinkage of the cooling rocks. The lodes are later than the dykes, which contain chimney-shaped ore-shoots; the ascent of the solutions was doubtless aided by the reheating due to the intrusion of the dykes.

The exploration of western Brazil was stimulated by reports of gold. The first successes were in 1699 and in 1718, when the discovery of the rich placers of Cuyaba led to the opening of the remote interior. The Passagem Mine at Ouro Preto, which was opened in 1817, occurs in gently dipping pre-Palæozoic quartzites. The main lode is a sheet of white quartz, which ranges up to 36 feet in thickness and is streaked with layers of tourmaline, pyrrhotite, and arsenopyrite. Below it is a dark tourmaline rock up to 3 feet in thickness, containing pyrite, pyrrhotite, arsenopyrite, and quartz. According to Derby the Passagem Lode is a pegmatite dyke intruded between the overlying Itabirite or banded ironstone, and the underlying quartzite, and subsequently impregnated with gold and sulphide. The lode is, however, probably a felspathic quartzite, in which pneumatolytic solutions altered the felspar into tourmaline and deposited the metals (cf. O. A. Derby, *Amer. Journ. Sci.* (4), xxxii, 1911, pp. 185-90; E. Hussak, *Z. prakt. G.*, vi, 1898, pp. 345-57).

Isolated Gold-Quartz Veins—Saddle- and Ladder-Lodes — The earth-movements in some goldfields instead of forming continuous fissures, produced isolated spaces, which have been filled by short lodes. The Bendigo Goldfield was discovered in 1851, and after its rich gravels were worked out search was made for the lodes whence the gold had come. Large quartz-"blows" were found, and some were so rich that they were broken up and crushed by hand hammers. These bodies of quartz proved to be wedge-shaped and they rapidly tapered out below. The view was therefore held that as the field had no persistent quartz-lodes like those of California the mines would be shallow. The mines are in Ordovician slates which have been corrugated by many parallel folds. As neighbouring quartz-blows sloped in opposite directions, it was suggested that each pair was the remains of a saddle or arch of quartz formed over a fold. This view was established by the Geological Survey of Victoria by E. J. Dunn, H. S. Whitelaw, and H. Herman, and supported by Rickard. The latest report is by H. Herman (*Bull. G.S. Vict.*, No. 47, 1923), who has shown that the field is a geosynclinal.

Saddle-shaped sheets of quartz were found one below the other where similar conditions recur. A shaft was sunk down the anticlinal axis, or "centre country," and while one saddle of quartz was being mined the shaft was carried down to the next saddle. The field, instead of being shallow, was mined to the depth of 4500 feet, and was for long the deepest goldfield in the world. The yield of gold declined with depth probably because the temperature was too high for rich gold deposition. In the neighbouring field of Castlemaine, the "diggings" were sensationally rich, but the lodes were disappointing and did not pay; the rich upper part had been removed by denudation, and its gold scattered in the drifts, and only the poor lower parts have been left underground.

The saddle reefs of Nova Scotia have been described by Malcolm (*G.S. Canada*, Mem. 20, 1912), but the ore is of low grade.

Ladder-lodes are isolated quartz-veins arranged like the rungs of a ladder at intervals across a vertical or steeply inclined dyke. The typical occurrences are in hornblende-porphyrite as at the Morning Star, Wood's Point. The dykes are in Silurian slate; as they cooled the shrinkage caused horizontal cracks which were filled with quartz, forming floors which in a vertical section of the mine resemble the rungs of a ladder. Occasionally, where the dyke was firmly frozen to the country, a crack would extend into the slate, and the quartz-floor project a few feet beyond the dyke. A small ladder-lode was worked at Little Bendigo, Ballarat. Less regular floors of quartz occur at the A1 Mines, where the gold was irregular in distribution, as it was introduced into the quartz-floors by superheated solutions which converted the porphyrite into propylite, and formed a mosaic of secondary quartz and felspar, epidote, zoisite, and chlorite. The gold occurs where the quartz-floors cross the propylitized bands.

Ladder-lodes also occur in the goldfield of Berezovsk in the Ural Mountains, in dykes of a microgranite known as beresite.

The Charters Towers Goldfield in Queensland illustrates a different disposition of isolated quartz-lodes. The country is a mass of granite enclosing a circular series of short radial fissures which have been filled by gold-quartz.

Impregnations and Replacements—Rhodesia, Home-

STAKE, ALASKA, AND PORCUPINE—In some goldfields the solutions, in the absence of fissures, percolated through irregular pores and spaces, and have thus produced impregnations of gold ore, usually with pyrite. These ores are usually low grade and have to be treated in bulk. Such impregnations occur in Rhodesia (*Tr. I.M.E.*, 1906, xxxi, p. 87) as mineralized schists along faults in the Gaika Mine, in diorite dykes in the Ayrshire Mine, in crushed granite, and in a complex of quartz-veins in a shattered mass of Banded Ironstones at the Wanderer Mine. These impregnations vary from rock with a sprinkling of auriferous pyrite to ore-bodies which have completely replaced the country rock.

The Homestake Mine at Lead in the Black Hills of South Dakota is famous for its vast bodies of low-grade ore in pre-Palæozoic rocks that were laid down as sandstones, dolomitic limestones, and clays, and have been altered by regional metamorphism into gneiss, garnetiferous-mica-schists, cummingtonite (an amphibole) and chloritic schists, quartzite, and crystalline limestone. The schists were bent into crowded and overturned folds. In the Keewenawan Period the area was intruded by amphibolite dykes, and worn down to a plain which was covered unconformably by Cambrian quartzites. The field was invaded by Eocene rhyolites and phonolites; a dyke of rhyolite was forced along the crest of the Homestake anticline, with minor dykes in all directions. Later the ground was again disturbed by earth-movements which fractured these dykes and formed along them layers of pug. The ore-bodies occur in the Homestake Formation, which consisted originally of magnesian limestone. The schists near the Eocene rhyolites are traversed by many "verticals," or thin seams of pyrites, pyrrhotite, and quartz.

According to J. D. Irving, the ores are pre-Cambrian, and provided the placer gold in the neighbouring Cambrian conglomerate. According to Hosted and Wright (*Eng. and Min. Journ. Press*, cxv, 1923, pp. 793 and 842) the ores are of Eocene age, and the gold in the Cambrian conglomerates is not alluvial, but was introduced by infiltration. The pre-Cambrian age of the Homestake ore is maintained by S. Paige (*U.S.G.S. Bull.*, 765, 1924, p. 42), who supports Irving's view and considers that the Kainozoic gold, some of which is telluride, can always be distinguished from the pre-Cambrian, and that as the local Kainozoic earth-movements were tensional, the shearing and crushing of the Homestake ore show that it must be pre-Cambrian.

The Alaska Treadwell Mine at Jumeau, an island off the coast of Alaska, is famous, like the Homestake Mine, for its long success in working low-grade material. The country is Carboniferous slate interbedded with altered lavas known as greenstones. Both rocks are intruded by albite-diorite dykes, which have been shattered by earth-movements and enriched with gold-bearing quartz and sulphides, including pyrite, stibnite, galena, blende, and molybdenite. Innumerable small veins ramify through the shattered diorite and form large bodies of ore, of the value of about 8s. a ton. Thanks to abundant water-power, the mines were worked on a great scale at the cost of about 5s. 6d. a ton. The difficulty in mining was the maintenance of such large excavations. Though the veins were usually a few inches thick, they were so crowded that the rock had to be removed for a width of 200 feet, and after the mine had been worked to the depth of over 1000 feet the timber pillars collapsed, the walls fell in and the mine was flooded by the sea.

The Porcupine Goldfield[1] is of interest as the youngest of the great goldfields, having been discovered only in 1909. It is in northern Ontario (48½° N., 81° W.), on the slope towards Hudson Bay. The field consists of Keewatin pillow lavas, with well-preserved variolitic surfaces, and tuffs. This series was followed by the Timiskaming sediments including sandstones, in which the false-bedding is often well-preserved slates and conglomerates. Both these series have been intruded by quartz-porphyry, which is also pre-Palæozoic. The relations of the rocks are well seen N. of the Dome Mine (Fig. 13) where the Timiskaming beds are gently folded into two anticlines and two synclines, and have at the base a thick conglomerate which rests on the lavas. The rocks at the mine are folded into an anticline with a gentle dip to the N., but a very steep dip to a compressed syncline on the southern side. Further S. is an extensive

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[1] A. G. Burrows, "The Porcupine Gold Area," 33*rd Ann. Rep. Ontario Dept. Mines*, Pt. II, 1925.

area of pillow lavas. The ore-bodies have replaced the sediments at the contact with the quartz-porphyry. The ore occurs in shoots, of which over 30 are known; a few are in the quartz-porphyry and the lavas, but most are in the sediments. The Hollinger Mine, which is now one of the world's great mines having up till 1923 produced £15,350,000 worth of gold, consists of a belt of Keewatin lavas which have been sheared and crushed into schist; nodules of unsheared rock can be found which show the variolitic structure. The intrusion of quartz-porphyry was followed by the deposition of many lodes which are sub-parallel to it, but sometimes cut across it. The lode material is mainly quartz, much of which encloses lava debris. A little poor ore has been found in the quartz-porphyry. According to Spurr the quartz-lodes are intrusive vein-dykes; but to the author they appear due to the saturation of a crushed mass of rock by solutions which deposited the quartz along the main channels of circulation.

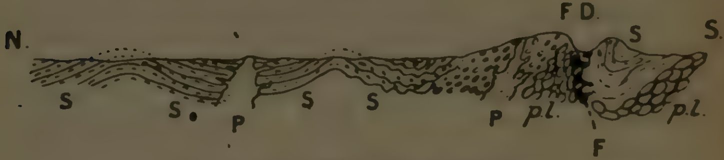

Fig. 13.—The Dome Mine, Porcupine.

The section across the country north of the Dome Mine, Porcupine Goldfield, Canada. S, gently folded sedimentary beds, slates, and quartzites, overlying conglomerates. Both are intruded by quartz-porphyry, P. The Dome Mine, D, with the ore-bodies (black) occurs along a fault, F, separating the sedimentary beds from the pillow lavas, *p.l.*, which form an extensive area south of the mine.

That the ore formation was deep-seated is shown by the abundance of tourmaline in part of the Dome Mine and the abundant tellurides including hessite (silver-telluride), altaite (lead telluride), and sylvanite and petzite (gold-silver tellurides). The tellurides in the Hollinger Mine were sparse in the upper levels, but abundant 800 feet deep.

The Goldfields of West Australia—West Australia consists of a plateau which rises from the coast by a mountain scarp to the height of about 1800 feet, and after extending far eastward at the level of between 1400 and 1200 feet, descends to the lowlands of Central Australia. The plateau consists of pre-Palæozoic gneiss and schists invaded by granites and acid dykes, and by basic intrusions some of which are now amphibolite and hornblende-schist. Some of the mica schists, chlorite schists, and slates were sedimentary rocks.

Gold was discovered in Kimberley in North-western Australia in 1882 and at Yilgarn, 200 miles E. of Perth, in 1887. Active mining followed the discovery of the gold at Coolgardie in 1892, but was delayed by the scarcity of water. That field proved disappointing as the gold is in shallow though rich patches. The mining fortune of Western Australia has been dependent mainly on the Golden Mile at Boulder, Kalgoorlie, which was discovered in 1895, and has been claimed as the richest square mile known in mining history. The treatment of the complex ores of Kalgoorlie, including sulphides, sulpharsenates, sulphantimonates, copper sulphides, and tellurides, was of exceptional difficulty, and was managed by the introduction to mining of many new processes, including the pebble-mill and filter-press. The lodes of quartz intergrown with black rock were regarded by E. F. Pittman (1898) as intrusive dykes; but H. P. Woodward (1898) explained them as due to the ascent through fissures of gold-bearing solutions which impregnated the rock on both sides. This view was confirmed (1898) by

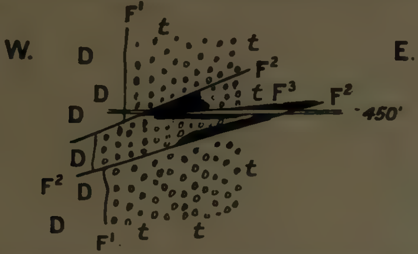

Fig. 14.—The Associated Northern Ore-Body, Kalgoorlie.

The Associated Northern ore-body, at Kalgoorlie (after Larcombe). The primary fault F^1 separates the dacite (D) from altered tuffs (*t*). The ore-body was formed in the tuffs in connection with two subsequent faults (F_2, F_3).

G. W. Card's microscopic examination of the ores, and R. J. Frecheville showed (1898) that the lodes had been formed along crushed zones. Some bands were still regarded as slates of sedimentary origin until shown by C. O. G. Larcombe (*Geol. Kalgoorlie*, 1913, pp. 77-82) to be sheared fine-grained varieties of the country, which is mainly quartz-andesite and granophyric dacite. Some altered tuffs show that the rocks were in part volcanic.

FIG. 15.—THE GREAT BOULDER LODE, KALGOORLIE.

The Great Boulder Lode, Kalgoorlie, traversing dacite, D, which has been altered by propylitization; s, lenticular bands of slate-like rock due to the shearing of the dacite. Ox., oxidized zone above water-level.

The lodes are of three types. In the N.E. of the field the Oroya-Brownhill lode is a curved sheet of quartz, which has been called a saddle-lode. The Associated Northern Mine is due to impregnation where dacite (quartz-andesite) is faulted against tuffs (Fig. 14). The third type, as in the Great Boulder Proprietary (Fig. 15) and Lake View Consols mines, consists of branching quartz-veins and sheaves of ore-lenticles in sheared country, which is slate-like aphanite and quartz-andesite. The sheared bands have been altered by hot water into quartz-sericite-carbonate rocks, with epidote and chlorite. The carbonates were formed by descending meteoric waters and were followed by silicification and shearing with the formation of secondary plagioclase; later the felspars and ferromagnesian minerals were converted to an aggregate of quartz, sericite, epidote, and chlorite. That the gold was probably introduced by deep-seated waters before these changes is shown by the abundance of telluride

Further N. in West Australia are gold mines of a simpler character, associated with quartz-veins and banded ironstones, and connected with granitic and basic intrusions.

Some of the mines are in rocks silicified along shear planes; others were probably bedded ferruginous clays and sands altered to ironstone and quartzite. The rocks containing the ores disappear to the N. beneath a sheet of Upper Palæozoic sandstone. Survey by the torsion balance, by tracing the buried granite and basic rocks, may indicate the course of any northern extension of the goldfields. Gold-bearing rocks outcrop further N. in Pilbara with a sedimentary series and conglomerates that have been described as similar to the Banket of the Transvaal; the alluvial gold in these conglomerates suggests the pre-Cambrian age of the West Australian ores.

SECTION B. SECONDARY ORES AND ENRICHMENTS

MT. MORGAN, QUEENSLAND—The early development of gold mining was hampered by the belief that gold would not be found far below the surface. This view was suggested by the rapid decrease in value of many gold ores when followed downward. This fall in grade is in many cases due to secondary enrichment (cf. p. 31) which has concentrated near the surface gold that had been spread through a great vertical range of lode. This secondary enrichment is most marked in countries which have remained above sea-level for long periods of time, such as West Australia and Southern India. In some of these fields the deeper part of lodes which are rich at the outcrop are too low grade to pay. An extreme case was that of the Londonderry Mine at Coolgardie. A hole 2½ feet deep, 6 feet long, and 5 feet wide showed £30,000 of gold; the claim was sold for £180,000, and floated as a company in London for £700,000. "The pocket" (Rickard, *Eng. and Min. Journ.*, 16 April, 1898) "did not continue even one foot lower." The vein below was repeatedly explored, but without success.

Secondary enrichment on a greater scale has formed some important mines, such as the Mt. Morgan Mine in Southern Queensland. The mine was opened on a hill 400 feet high, composed of a mass of quartz so cavernous and stalactitic that it was described by Jack as the sinter of an ancient geyser, resting on slate and quartzite. Hot waters had leached the gold so thoroughly that it was the finest that has been found and contained 998 parts of gold in 1000. The microscopic structure of the quartz gives no support to the geyser theory. The mine (Fig. 16) is on an ancient volcano, as observed by the author in 1909, as the quartzite proved to be quartz-porphyry and the slates to be volcanic tuffs and altered spherulitic basalt with crusts of variolite. The formation of the mine began during the Palæozoic (Newman and Campbell Brown, *Tr. Austral. I.M.E.*, xv, 1911, p. 443) with the injection of a complex series of dykes, followed by the intrusion of diorite which so weakened the crust that the igneous rock reached the surface and established a volcano. Its base was intruded by a second series of dykes and after the volcano became extinct, the rocks were saturated by waters which deposited sulphides of iron and copper rich in gold. The plutonic origin of these waters is indicated by the presence of tin oxide, cassiterite. A large mass of pyrites was deposited by replacement beside the volcanic pipe. The country was worn down to a peneplane on which was deposited the Upper Cretaceous Desert Sandstone, which contains placer gold from the mine. As the country was lowered by denudation, surface waters dissolved silica, gold, and iron oxide and re-deposited them as the rich gossan. The upper part contained 3 oz. of gold to the ton; the lower part of the open-cut was enriched to 6 oz. to the ton, below which the grade fell to 1½ oz. Pyrite was deposited below the enriched oxidized belt, but the copper was carried lower and deposited in the underlying pyritic ore-body beside the

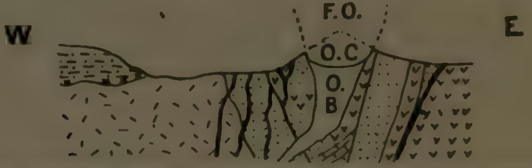

Fig. 16.—Section across the Mount Morgan Mine, Queensland. The ore-body (O.B.) traverses mainly variolitic diabase (V) which is associated with a band of limestone and quartz-porphyry (dotted). To the west is an area of old granite covered by Desert Sandstone with placer gold (X) indicating the pre-Cretaceous age of the ore-deposits. O.C. is the open cut; black lines, diabase dykes. F.O. former outline of the hill.

root of the volcano. This ore contains about 6 dwt. per ton of gold and 2½ per cent. of copper; the mine which in its early days contained the purest of recorded native gold ended as a low-grade copper mine yielding gold as a bye-product.

Section C. Alluvial Goldfields

Placers—Alluvial deposits or placers (cf. p. 32) and their altered representatives are especially important in gold mining, though the same methods are applied to placers containing tin and platinum. The first economic process of working low-grade placers was by hydraulic sluicing which was developed in California. Water is impounded in a high level reservoir and brought to the alluvial deposit by a lead or trench; it falls through an iron pipe to a nozzle, which directs it against the gold-bearing material. A "Giant" nozzle weighing 2000 lb. can control a stream with a head of 500 feet; the water leaps from it with a velocity of sometimes 2 miles a minute, and in a jet so strong that a stick may be broken across it as over a metal bar. The jet digs into the gravel, and washes the material along a chain of sluice boxes, on the floor of which the gold is caught in between ridges or "riffles," or on canvas, or by mercury. The chain of sluice-boxes may be from 100 feet to miles in length.

This process is most effective in working gravels about 80 feet thick; if the beds are thinner, time is lost in frequent movements of the nozzle; if the beds are thicker the material falls in unmanageable masses and for safety the nozzle has to be too far from the cliff for the jet to have its full excavating power. Thicker beds have therefore to be worked in two layers. The cost of hydraulic sluicing is low, and in California is from 1½d. to 6d. per cubic yard. Hydraulic sluicing has been successfully used in alluvial fields in most parts of the world.

Dredging is usually the cheapest method of working a low-grade placer in river valleys. The first device was a floating timber platform, on to which gravel from a river bed was shovelled by a man standing in the water, or by a spoon dredge worked from a boat. Another hand system was to drop a bucket on to the river bed and haul it ashore. In 1882 McQueen, a New Zealand miner who has been called the "Father of Dredging," proposed the use of the harbour bucket dredge, and one was tried on the Otago River in 1886. It was not a financial success but showed that the process was practicable, and specially designed bucket dredges proved efficient and extraordinarily economical. It is claimed (E. B. Wilson, *Hydraulic Mining*, 1898, p. 100) that ground less than 60 feet below or 20 feet above water-level, which does not contain boulders more than a ton in weight, should be handled by dredges at 1½d. to 2½d. a cubic yard, though the cost is often 5d. a cubic yard. Wilson (*ibid.*, p. 106) states that a dredge may pay on a recovery of ¾ of a grain of gold to the ton of gravel, and some have paid dividends in Victoria with material of that grade. A dredge may haul from a river a cubic yard of earth, wash it, separate its gold, and yield a profit if it contains a pennyworth of gold.

In some rocky river beds the gold lies in the depressions and a bucket dredge can only recover it by breaking off the projections unless the river bed has been blasted, so that the material can be scooped out. Such places can be worked by the suction dredge, which by a stream of water sucks up a pipe all loose material and gold dust on the river bed. Suction dredges are also used on river-side flats; the dredge is built in an excavation; it works forward, depositing the ground washed from the front of the pit behind it; it is floated forward to a new position by flooding the excavation, and thus gradually works its way through the whole alluvial plain. The coarse boulders should be deposited at the bottom and the fine material on the top, so that the ground may be left in better condition for agriculture than before the dredge began its work.

Deep Leads—The river placers first worked lay on the beds of rivers or the floors or sides of valleys and were known as "leads." Some exceptionally rich deposits were due to a recent valley having been cut through the deposits of an older valley, with the reconcentration of its gold. Thus (at XX in Fig. 17) the gravel was especially rich because that of an ancient river had been rewashed and the gold further concentrated. The continuation of the old river was found under the hills of sand and clay which have filled its valley, and is a buried lead or "deep lead."

A deep lead must be 100 feet deep according to Victorian law, or over 20 feet deep by that of Western Australia. The richness of the drifts at Golden Point was due to the river having cut through the indicator belt of Ballarat East (cf. p. 40) and to the repeated rewashing of the gravel as the valley was deepened and enlarged. The leads on the western slopes of Ballarat East disappeared at the foot of the plateau of igneous rock which was called "hypogean trap;" as it was regarded as deep-seated, there appeared no chance of the leads passing beneath it. This wall of rock blocked progress, so the miners named it Sebastopol—the Crimea war being then in progress. Meanwhile in the neighbouring field of Creswick it was found that a lead continued under a similar igneous rock, which was therefore a sheet of lava and not a deep-seated mass.

Fig. 17.—A High Level Deep Lead.

A dissected high level Deep Lead. A modern river, AA, has cut its valley between two hills—contours at 200 and 300 ft. A Deep Lead flowing from 190 ft. at the eastern end to 170 ft. at the west has been cut through by the modern river, and rich gravels occurred at XX where the gold from the old river gravel had been redeposited.

This success led the Ballarat miners to renew their siege of the Sebastopol plateau; they mined underneath it and found that the leads from Ballarat East continued westward under five lava flows, and joined the main lead of the river that drained the area before the volcanic eruptions. The working of this lead was impossible while alluvial miners were allowed claims of only 20 feet square. By successive concessions the mines were enlarged to prospecting areas of 1000 acres and ultimately leases of 5000 acres. This enlargement of the claims rendered possible boring across the

Ballarat plateau to determine the position and depth of its main lead, of whose meandering course there was no indication on the surface.

These bores initiated deep-lead mining, which depends largely on geology both for the tracing and working of the leads. Western Victoria includes a great plateau across which in Middle Kainozoic times rivers flowed southward to the Southern Ocean, and northward to the Murray River. Numerous volcanoes discharged sheets of basalt, which filled the valleys on the plateau. Subsequent denudation has removed the softer rocks which formed the banks of these valleys, and the lava flows have been left upstanding as plateaus (Fig. 18). The ancient river beds lie under the basalt and as they flowed over rocks containing many gold-quartz lodes, the river gravels contain alluvial gold. The profitable mining of these gravels required accurate knowledge of their position and depth. The Geological Survey of Victoria therefore made lines of bores across the basalt plateaus to determine the course of the ancient river system, the tracing of which was an interesting problem in physical geology and yielded many surprises. The bore records are used to construct a section showing the varying level of the bedrock, and the height and position of the river bed. Its

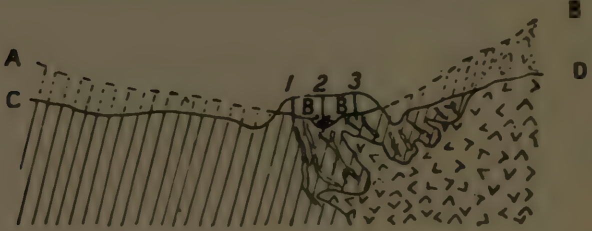

FIG. 18.—A SECTION ACROSS A DEEP LEAD.

BB, basalt plateau overlying a former river bed reached by No. 2 of the three bores, 1, 2, 3. The country at the right end of the section is granodiorite sending up tongues which are associated with auriferous quartz-lodes in the slates and quartzites of the country. AB, the former outline of the valley, on the floor of which the basalt lava flow was discharged. CD, the present surface with river valleys formed on either side of the basalt plateau.

height at different lines of bores indicates the river gradient, from which can be inferred the amount of meander between the two lines, and where the current would have been sufficiently powerful to concentrate the gold. The samples from the drill holes indicate the relative amount of gold, but not the actual yield, for they are a concentrate, much of the lighter material having been washed away during the drilling.

A deep lead cannot be worked until it has been drained. A shaft is sunk to a suitable depth below that of the lead. A drive known as the "reef drive," as it is in the bedrock, is made under the lead, which is drained by bores put into it from this drive. Some mines had to pump several million gallons of water a day for years before it was possible to enter the lead. Lead mining under favourable conditions has been very profitable; the Madame Berry Mine, e.g. paid £1,300,000 in dividends on a capital of £15,000. When part of the lead is drained it is entered by the upper or "wash drive," from which the gravel or "wash" is dropped through shoots to the reef drive, whence it is raised to the surface. The gold is washed out of the sand; none is found in the pebbles.

The costs of working are estimated per square fathom, as most of the gold is in the lower part of the gravel, and the yield depends more on area than on thickness.

The probable value of a lead depends on constant re-enrichment, as the gold usually travels but a short distance. A lead which crosses rocks intruded by granodiorite and likely to contain numerous gold-quartz veins, may be expected to be richer than areas without igneous rocks.

The distribution of the leads depended on the nature of the plateau basalts, and the mining has shown that they were formed by the confluence of lavas from many vents and not by eruption from fissures.

The Kanowa Lead in Western Australia, as its gold has been dissolved and redeposited, raised the question whether the mines had to comply with the regulations for alluvial or lode mining. Though the evidence proves that the gold as it now occurs, was deposited from solution, it has been wisely treated as alluvial. The problem bears on the nature of the gold of the Rand (cf. p. 61).

RAND BANKET—Marine placer deposits occur on the coasts of New Zealand and at Nome in Alaska: but the most important is the Witwatersrand Goldfield in the Transvaal, the most productive goldfield in the world. The South African goldfields have been worked from prehistoric times in Rhodesia, which is often regarded as the Ophir, whence Solomon obtained the gold for his temple. The gold in the Rand ore, though very rich, is in such minute particles that it is rarely visible and produced no noticeable alluvial deposits. The ore was discovered in 1885, at Langlaagte, near Johannesburg, and the auriferous conglomerate was followed during 1886 for miles E. and W. Johannesburg was founded in 1887. A boom in 1888 was followed in 1889 by a panic due to the discovery that much of the ore was low grade, and that the minuteness of the gold rendered its recovery difficult by the methods then used. The local coal discovered in 1887, the regularity of the ore in bulk, and the opportune discovery of the cyanide process, rendered the mining easy and profitable.

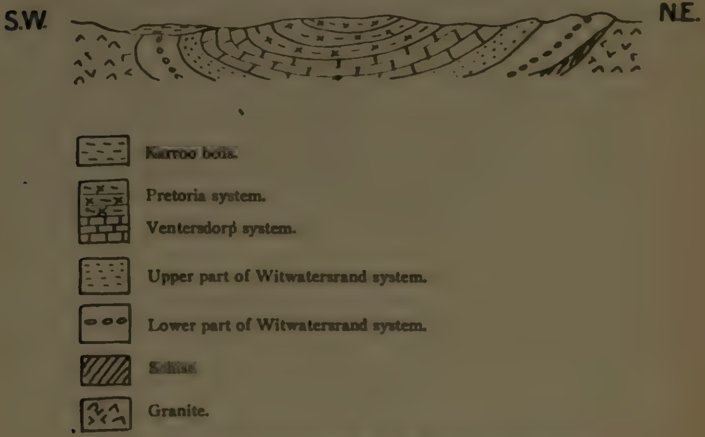

Fig. 19.—Section across the Rand Goldfield.

The Rand Goldfield is a large synclinal basin (Fig. 19) of pre-Palæozoic rocks. Both to N. and to S. are granites, of which the northern is intrusive into schists containing quartz-veins. The granite and schists are covered unconformably by the quartzites, slates, and conglomerates of the Witwatersrand System. The thicker beds of conglomerate are known as Reef; the thin beds which have undergone prolonged wave action are known as the "Leaders" and are the ore or "Banket." That name has the same root as banquet, and was given to the rock either from its resemblance to the sweetmeat, hardbake, or to the bread containing raisins used by Boer farmers when travelling. The typical pebbles in the Banket are somewhat bun-shaped, as they have been swept to and fro by the tide until the lower side was worn flat and the upper side smoothed by the wash of sand over it. The pebbles may be 10 inches high where the Leader is only 3 inches thick, so that they project above it. In the upper part of the Rand System some conglomerates, that rest unconformably on the gold-bearing reefs, contain pebbles of gold-bearing Banket, which therefore received its gold before the deposition of the overlying conglomerates. Above the Witwatersrand System, and separated from it

Fig. 20.—Section of Main Reef Leader.

Section of specimen of the Main Reef Leader of the Meyer and Charlton Mine, Johannesburg, × 25 dia. Under the edge of the pebble which occupies the upper part are grains of quartz, and three crystals of pyrite (marked by horizontal lines). In the cement are numerous particles of gold—black lines and dots. The slide is cut from a sample containing 1383 dwt. to the ton. The matrix is no more altered than adjacent Banket containing 2 dwt. to the ton.

by a marked unconformity, is the Ventersdorp System with a vast series of basic lavas; during their eruption the Rand was invaded by many dykes. The lavas were followed, after another unconformity, by the dolomites of the Pretoria System, which occupy the central part of the Rand syncline.

The Banket (Fig. 20) contains much pyrites, which often forms 3 per cent. of the rock, and is mostly in small crystals and grains, or thin seams or streaks. Arsenical pyrites is absent. The mineral which is most conspicuous in microscopic sections after the pyrites and quartz, is chloritoid (Fig. 21), which has developed *in situ* and is usually a product of high pressure. A little mica is present and due to the decomposition of felspathic matter. The rarer constituents include chalcopyrite, blende and galena, grains of rutile, zircon, corundum and tourmaline, and still more rarely diamonds, platinum, and osmiridium.

FIG. 21.—MAGNIFIED SECTIONS OF BARREN AND RICH CONGLOMERATE FROM THE RAND.

(*a*) Barren angular grit with a base of sericite schist, a crystal of chloritoid (*ch.*) and pyrites (black) × 60 dia.

(*b*) Section from the Main Reef Leader showing edge of a quartz pebble, rounded and broken quartz grains, pyrites (solid black), and particles of gold (opp. *g.*) × 60 dia.

The occurrence of the gold in conglomerate at first suggested its placer origin; but when it was found that the gold was always in the cement and not in the pebbles, this view was generally abandoned and the gold attributed to infiltration, as in ordinary lodes. The restriction of the solutions to the conglomerate was attributed to its being more permeable than the sandstone. It was also pointed out that the gold particles are minute, and that they and the pyrites are angular and not water-worn, and that the rounded pyrites might be concretionary. It was also claimed that as the Rand gold contains from 100 to 120 parts per 1000 of silver, it cannot be alluvial. On these grounds the gold was attributed to Ventersdorp age, when the Rand beds were intersected by dykes, against which a patch of rich ore may end abruptly. (The latest full statement of this position is by C. B. Horwood, *Gold Deposits of Rand*, 1917.)

These arguments are however inconclusive. Gold in placer deposits occurs in the cement and not in the pebbles, which represent the hard barren "buck-quartz." Some placer gold, as in Queensland, contains 50 per cent. of silver and is of much lower grade than that of the Rand. The angularity of the gold is due partly to its having been squeezed between the grains of sand, and partly to the gold having been dissolved and redeposited. The sudden ending of rich patches against a dyke is due to its rise along a fault; the abrupt termination of the patch is due to the fault.

Fig. 22.—A Pyritic Pebble from the Banket.

A pyritic pebble from the Banket with wind-shaped surfaces, pseudomorphic after a pebble of iron oxide. The pebble is half-an-inch in width.

The placer theory of the Rand was faced by two difficulties —the rarity of pyrites in ordinary placers, and the rich concentration of such minute particles of gold. Pyrites occurs in placers containing abundant vegetable matter, but not in quartz sands where it would be destroyed by oxidation. The Rand pyrites however often occurs in streaks and patches like black iron sand on a sea beach; the Rand pyrites was probably deposited as iron oxide. Some of the larger pebbles of pyrites (Fig. 22) have sand-worn faces, and must have been originally pebbles of either ironstone or quartz which has been replaced by pyrites.

Gold in particles as minute as those in the Rand occurs in sands and silt, but rarely amounts to more than a pennyweight or so per ton; whereas some Banket contains over

1000 oz. to the ton. The concentration of this gold is probably due to each seam of Banket having been formed during a long pause in deposition, so that the layer was subjected to prolonged wave action, during which the gold was collected in the hollows between the pebbles, as in the riffle of an ore-concentrating plant.[1] The beds of "false banket," or "bastard reef," in which the pebbles are angular, accumulated quickly, and gave no opportunity for such concentration of the gold; and they may contain only a few grains or 1 or 2 dwt. per ton of gold, although in all respects, other than those due to long-continued beach action, they are identical with a rich underlying leader. The concentration of gold by water action is also shown by the so-called "shoots" in the East Rand. They consist of gravelly stream beds across the beaches; and the flow of water down these pebbly channels concentrated gold in them.

The minerals found in the Banket include diamonds, platinum, tourmaline, corundum, osmiridium, and zircon, and they are characteristic of alluvial deposits. The typical hydrothermal minerals are absent.

If the ore had been formed by infiltration, it is improbable that the gold solutions would not have occasionally passed into the bastard reef, which in many places must have been at least as permeable as the Main Reef Leader.

The Banket has been worked more extensively than any other gold ore, and the sections have been most carefully sampled and studied; yet no case has been described of any infiltration channels, like the verticals of Dakota, by which the gold could have been introduced.

That the gold was introduced during the deposition of the conglomerate, and not during the injection of the dykes at the long subsequent Ventersdorp period, has been shown where contemporaneous erosion has left a patch of the gold-bearing Banket surrounded by quartzite; the first case was recorded from the May Consolidated Mine (Gregory, *Tr. I.M.M.*, xvii, 1908, p. 21; confirmed by E. T. Mellor, *J. Chem. Met. Soc. S. Afr.*, 1916, xvi, p. 158).

The placer theory of the Rand was adopted amongst

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[1] E. T. Mellor however regards the Banket as formed by sudden floods, a view rejected by R. B. Young, *Journ. Chem. Met. Soc. S. Afr.*, 1916, xvi, p. 230; and by du Toit, *Geol. S. Africa*, 1926, p. 66.

others by Becker (*Ann. Rep. U.S.G.S.*, 1896-7, pp. 163-7), and restated with explanation of the two chief difficulties by the author in 1907 (*Tr. I.M.M.*, xvii, pp. 2-41). It has been fully confirmed by the detailed survey of the field by E. T. Mellor (*Tr. G. Soc. S. Afr.*, xiv, xvi, xviii, 1911-15) of the Geological Survey of South Africa, and the work by R. B. Young (*The Banket*, 1917). The Banket of the Gold Coast is also a placer, according to Sir A. E. Kitson (*Gold Coast G.S. Bull.*, i, 1925, p. 8).

The future of the Rand depends on the depth to which the Banket can be mined, and the field has the great advantage that the rise of underground temperature is abnormally slow. Mining has already reached the depth of 7000 feet in the Village Deep Mine, and plans have been prepared for its extension to 10,000 feet, which will be more accessible on the Rand than elsewhere, owing to the slow increase of underground temperature.

The gold was probably derived from gold-quartz veins near the granite-schist contact that passes N. of Johannesburg; and, as a granitic mass is exposed on the southern side of the Rand basin near Vredeport, the contact zone there may have contributed gold to the beds in that district. As the gold particles are exceptionally small they may be widespread. Attention has been called by J. B. Tyrrell (*Tr. I.M.M.*, 1916, and *Econ. Geol.*, xii. pp. 717-21) to an analogous case of the occurrence of placer gold in minute particles in the Upper Cretaceous Edmonton Sandstone of Alberta; the gold was derived from a distant range in British Columbia and only the smallest particles reached the sea. This gold has only been concentrated to a payable grade where recent rivers have cut through the sandstone; there was no widespread tidal action as on the Rand.

Morro Velho—The Brazilian mine, Morro Velho in Minas Geraes, is one of the most interesting in the world. It is worked by the St. John del Rey Mining Co. which was founded in 1830. The mine has an extensive literature, including Miller and Singewald (*Eng. and Min. Journ.*, cii, 1916, pp. 207-12); Hussak (*Centralbl. f. Min.*, 1902, pp. 69-92); A. F. Calvert (*Min. Res. Mines Geraes*, 1915). It is now 7000 feet deep and is one of the two deepest of existing mines. Its ore differs from that of any gold-quartz lode by maintaining its value to such great depths. The ore-body has the shape of a flattened pipe with an average thickness of 10-12 feet., a maximum of 33 feet, and a width of usually less than 600 feet, though in places of 1000 feet. It is in a bed of chloritic schist which is probably altered calcareous clay. The bed is vertical, and the pipe of ore lies along it at an angle of 45° to the horizontal. The ore consists of sulphides, especially pyrite, pyrrhotite, and arsenopyrite, with a little chalcopyrite, and a matrix of siderite, quartz, dolomite, and calcite, with some carbon and fragments of the chloritic schist. The gold is rarely seen as it is present in the arsenopyrite. The ore was foliated after the mineralization, and the sparse vein-quartz is barren. There is no evidence of much earth-movement, such as faulting, and no pug along the ore. The lower levels are quite dry and the lode has no deep-seated minerals, such as tellurides or tourmaline. There is also no clear evidence of the infiltration of solutions, and the ore has maintained its value as deep as it has yet been followed.

This lode was probably a placer containing alluvial iron oxide and fine-grained gold ; when the sediments were foliated into chloritic schist, the iron minerals were converted into sulphides, and the gold dissolved and redeposited with the arsenopyrite. This view is consistent with the continued richness of the ore in depth, its mineral character and microscopic structure, and absence of infiltration channels.

CHAPTER IV

ORES OF PLATINUM

Platinum—Qualities and Distribution—Platinum (Pt.; at. wt., 195; sp. gr., 21·5; melting-point, 3200° F.) was named from its resemblance to silver (diminutive of Spanish-Plata). It is exceptionally heavy, and owing to its high melting-point and resistance to most acids and oxidation, is of special value in many chemical, electrical, and industrial processes, and for jewelry. Platinum owing to its scarcity and unique qualities, is now the most expensive of ordinarily used metals; its price has risen from 8s. an oz. in 1870 and £3 an oz. in 1900, to £25 per oz., or five times the value of gold. Platinum has been found in the nickel-iron meteorites, and, being one of the heavy metals and associated with deep-seated igneous rocks, is probably a constituent of the nickel iron core of the earth. It has been widely regarded as an igneous mineral, and as a primary constituent of ultra-basic rocks. In many cases it is of hydrothermal origin, and even in ultra-basic rocks is sometimes a secondary constituent.

Platinum, though scarce in quantity, is widely distributed; most of its occurrences are where basic igneous rocks have been raised to the surface by mountain-forming uplifts, and usually those of the Altaid System. Its only British occurrences are in Southern Ireland and Cornwall. It has been found in most European countries. Russia has been the main producer, and yielded in 1914 over 90 per cent. of the world's supply. Platinum occurs in Burma, Central Asia, and Japan. In North America it has been found in many places among the Western Mountains, and along the Appalachian Mountains, while Sudbury in Canada supplies most of its only important compound, sperrylite ($PtAs_2$). South America was its original home. In South Africa it occurs with ultra-basic rocks, as in the Urals, and in quartz-veins. It is widespread in the Eastern Highlands of Australia and is found in New Zealand.

Platinum is usually obtained from alluvial deposits, in which it collects owing to its heaviness and resistance to weathering. Some alluvial platinum is derived from sedimentary rocks, as from slates in Germany and New South Wales; but most of it has been derived from basic and ultra-basic igneous rocks, and especially from the chromite-olivine rock, dunite.

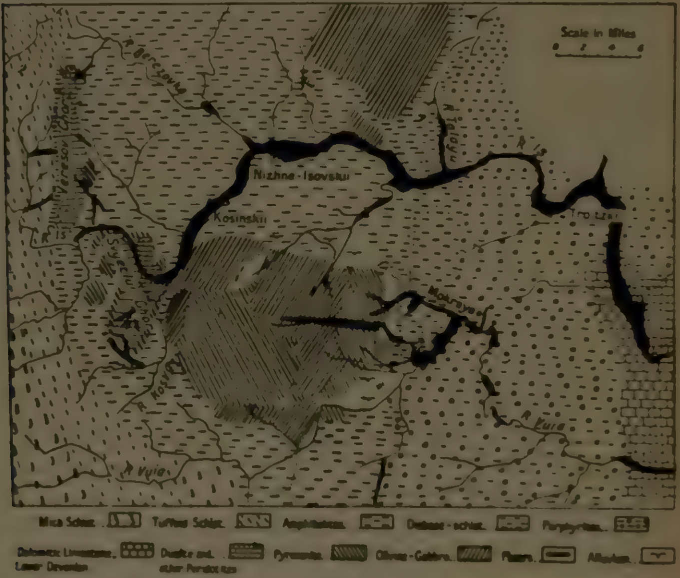

FIG. 23.—THE PLATINUM PLACERS OF THE IS RIVER.

The platinum placers of the Is River, the Urals, after N. Vuisotzkii, 1913. (Ghor = mountain.) The district is around 58⅞° N., 59¾° E.

URAL MOUNTAINS—The platinum deposits of the Ural Mountains are the most important. Those mountains consist of pre-Palæozoic gneiss, schist, and quartzite, followed by marine Devonian, Carboniferous and Permian. The igneous rocks include pre-Devonian granite and porphyry; granites and porphyries intrusive into the Devonian; syenite-porphyrites, quartz-keratophyres, and aplites that are Carboniferous and perhaps partly Permian. The characteristic igneous rocks of the Urals are serpentines and dunites, which are intrusive into the Lower Devonian limestones, and basic diabases, which range in age from the pre-Devonian to Upper Carboniferous or Permian.

The Urals were compressed by mountain movements after the Artinskian (Upper Carboniferous), and some of the folds have been overturned westward. The dunite was at first regarded as the only parent rock of platinum, but it is also found in olivine-pyroxenite, gabbro, and serpentine. The placers from which the main supply is obtained (Fig. 23) rise on the dunite masses. In pyroxenite, according to Duparc and Tikonowitch (1920, *La Platine et les Gîtes Platiniferes de l'Oural*, p. 80), the platinum " generally forms a local cement between the crystals of pyroxene;" it is often found in nodular segregations of chromite; in the dunite it is seen " excessively rarely" (*ibid.*, p. 193). The platinum is doubtless of deep-seated origin; but as it in part replaced the chromite and ferro-magnesian minerals, and has been moulded on the olivine and pyroxene, Beck truly described the platinum as the last formed mineral in the rock (Fig. 24).

FIG. 24.—PLATINUM IN PYROXENITE.

Platinum in pyroxenite replacing and corroding the pyroxenite, P; from the Urals. (After Duparc and Tikonowitch, 1920.)

SOUTH AFRICA—The Transvaal is expected to become the chief producer of platinum, as it includes large deposits, estimated to contain 5 dwt. to the ton, at Lydenburg in the

Transvaal; the ore is at two horizons in the pre-Palæzoic basic rocks of the Bushveld Complex. The lower horizon is a thick band of silicified serpentine which, according to P. A. Wagner and E. T. Mellor, is an altered dunite containing a variety of olivine, hortonolite. This dunite occurs in veins and nodules and is traversed by veins of quartz, chalcedonic silica, and magnesite, so that it has been subject to hydrothermal action. A pegmatite—with black hornblende crystals 3 inches long, and diallage, phlogopite, and magnetite—is associated with the hortonolite-dunite.

According to Stanley and Wagner (*J. Chem. Soc. S. Afr.*, xxv, 1925, pp. 254-9) the platinum is a primary constituent of the dunite; but it frequently occurs as irregular interstitial grains that solidified after the other constituents.

The upper horizon of platinum is in a diallage-norite that contains pyrite and chalcopyrite, which are presumably secondary.

A third platinum occurrence in the Transvaal is in a quartz-lode in the Waterberg Sandstone (pre-Cambrian). This lode has been formed by solutions circulating along a fault, which is post-Karroo and therefore post-Lower Jurassic. Some of the platinum is a replacement after pyrite. The ore has yielded about 2½ dwt. to the ton.

Platinum has been found in Rhodesia with sulphides in a long dyke-like band of diallage-norite at Makwiro. The rock contains up to 3 dwt. of platinum to the ton, but the particles are said to be so minute that they float on water and cannot be recovered by washing. R. S. Lightbody (Rep. 19, *S. Rhod. G.S.*, 1926) remarks that the presence of the platinum is not easily explained, as it is not in the heaviest of the norite.

British Columbia—Platinum has been found at Tulameen in the Rocky Mountains of British Columbia in a Jurassic magnetite-olivine-diallagite (koswite), which has been hydrothermally altered (Poitevin, *Canada G.S.*, *Summ. Rep.*, 1913, pp. 84-101). The koswite surrounds masses of dunite, which also contains platinum.

Genesis of Platinum Ores—As chromite, the mineral most often associated with platinum, is an essential constituent of dunite, the view has been adopted that platinum is a primary constituent of that rock, and is normally of igneous origin. Platinum, however, is found in a great variety of rocks and usually in those that have undergone hydrothermal alterations and contain secondary sulphides. It is associated with serpentine, an altered ultra-basic rock in the Urals and British Columbia. In South America, in Columbia, where platinum was first discovered and which has been second only to Russia in output, it comes from gabbro along the Choco River and is found as nuggets intergrown with chromite on the Condoto River. In New Zealand alluvial platinum has been derived from dunite, and in Spain from peridotite. It occurs in diorite in Walhalla, Victoria; in quartz-monzonite and pegmatite in Nevada; in pyroxene-syenite at Franklin, British Columbia; and in altered bands beside basic intrusions in Mexico. It is generally associated with chalcopyrite and pyrites as at Lydenburg, Sudbury, and Franklin, British Columbia, and with gold, silver, and copper ores as at Walhalla. It is in many places a constituent of quartz-veins, as in Nevada, the Waterberg Sandstone in the Transvaal, the Gympie goldfield in Queensland, and New Zealand. In Nevada, near the Boss Mine, platinum was introduced with copper minerals along fault planes, probably in Carboniferous times after intrusions of quartz-monzonite. It is frequently found in nuggets, which weigh up to 25 lb. in the Urals, and over 3 lb. in Columbia; and nuggets are usually due to secondary concentration. The introduction of platinum by solution has been claimed by L. Hundeshagen (*Tr. I.M.M.*, xiii, 1904, p. 550), for the ore at Sepongi in Sumatra, for an intrusion of granodiorite that produced wollastonite and garnet, was followed by the entrance of solutions carrying platinum, copper, and gold.

The age of the chief platinum occurrences is Upper Palæozoic. The pre-Palæozoic coigns of gneiss and schist have yielded no platinum of commercial importance. The igneous rocks of the Urals that contain platinum are post-Devonian; those in Nevada are late Carboniferous or Permian. The age of that in the Waterburg Sandstone of the Transvaal is post-Karroo (i.e. at least post-Triassic). The most numerous other occurrences are in western North America, in the northern Andes in Columbia and Equador, the Appalachian Mountains of the eastern United States, the Hercynian folds of Germany, France, and Spain, and along earth-movements of the same age in the Eastern Highlands of Australia. That platinum was raised in solution is suggested by the fact that the ultra-basic rocks in which it is found have been strongly altered, by its occurrence in various intermediate and sub-acid rocks, and with metallic sulphides in quartz-veins. The fact that the metals with which it is associated are mainly copper, gold, and chromium, in addition to its own kin, such as osmium and iridium, indicates that the solutions which carried the platinum were of deep-seated origin.

CHAPTER V

ORES OF TIN AND TUNGSTEN

TIN ORES[1]

TIN—HISTORIC INTEREST—Tin (Sn from Latin *stannum*—the English name comes from the Greek, *zinn ;* at. wt., 118 ; sp. gr., 7·1 to 7·3 ; melting-point, 450° F.) the white metal, is of special historic interest from its influence on early culture and prehistoric trade ; most of the Mediterranean supply was obtained by the Phœnicians from Cornwall. The present main use of tin is in " tinned plate," as a thin film preserves iron from rust and corrosion.

PNEUMATOLYTIC ORIGIN—Tin is obtained from cassiterite (SnO_2), which occurs in altered granites. It has been prepared artificially by passing stannic fluoride (SnF_4) with boric acid over hot lime ; it was probably mainly formed by the decomposition of stannic fluoride (SnF_4) by boric acid, producing tin oxide and some borate such as tourmaline. Many occurrences, however, such as stalactites, impregnations in buried timber, and pseudomorphs after felspar, are due to deposition from solution, as tin oxide is slightly soluble in boiling water.[2] Tin pyrites or stannite, a mixed sulphide of copper, tin, and iron, has been mined in Cornwall, New South Wales, and Chile.

Cassiterite being heavy and resistant of weathering remains as a residual mineral in alluvial deposits. It generally pays to mine only where concentrated by denudation of tin-bearing granites. Tin ores of commercial value are remarkably restricted in distribution (Fig. 25). The chief fields are

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[1] For the tin fields of the world and a full bibliography, see W. R. Jones, *Tinfields of the World*, 1925.

[2] Cf. Collins, *Miner. Mag.*, iv, 1880, pp. 1, 103 ; v, 1883, p. 121.

FIG. 25.—THE DISTRIBUTION OF TIN ORES.

Five chief fields are marked by large black dots; the less important occurrences and records are shown by smaller dots. The occurrences are all near parts of the Altaid or mountain movements of the end of the Palæozoic.

Cornwall, Malaysia, including the islands of Billiton and Banka, and adjacent areas in southern Burma, Siam, and Yunnan; also in north-western Tasmania, Bolivia, and Nigeria; small deposits have been found in Germany, New South Wales, and Alaska. No important supplies have been found in North America.

Cornish Mines—The tin-field of greatest historic interest is Cornwall, which was worked by the Phœnicians about 1000 or 600 B.C. They cast the tin into cross-shaped ingots weighing about 150 lb. each, that were well adapted for transport on horseback and on the floor of a boat. The stream tin is derived from lodes which are generally associated with masses of Carboniferous or Lower Permian granite and quartz-porphyry dykes, both of which were injected when the Lower Palæozoic rocks of Cornwall and Devon were folded by mountain-forming movements. The predominant rock is slate, locally known as killas, in which the lodes contain ores of copper; but when the lodes pass down into granite the copper is replaced by tin (Fig. 9, p. 21). Dolcoath Mine, which was 3 miles long and 3000 feet deep and is the deepest of British metal mines, was begun for copper; the workings entered granite at the depth of between 120 and 1500 feet, and were continued for tin. The primary tin ore occurs mainly in the vein-quartz of the lode; but it in places impregnates the granite walls thus forming the "capel."

The significant minerals associated with tin ores contain boron and fluorine; they include tourmaline, a complex variable borosilicate ($(AlB)_2SiO_4 + x$), topaz, the fluosilicate of aluminium ($(AlF)_2SiO_4$), and fluor-spar (CaF_2). The felspar beside the tourmaline veins has been altered to kaolinite (p. 169). The Cornish tin lodes were formed under pneumatolytic conditions by the attack of superheated steam with boric and fluoric acids upon the felspars and their conversion into tourmaline, topaz, and kaolinite, while the quartz was corroded, and cassiterite deposited. Where lime was present the fluoric acid formed fluorite. Primary tin ores throughout the world have this pneumatolytic origin, with local variations.

Mt. Bischoff, Tasmania—The Mt. Bischoff tin mine in northern Tasmania was discovered in 1871; mining was begun in 1873, but was delayed by the heavy rainfall, which ultimately helped by providing cheap water-power. The country (Fig. 26) consists of slates and quartzite of Cambrian or Ordovician age; in Devonian times they were folded and intruded by masses of granite and ring-dykes of quartz-porphyry. The mine is situated among a group of altered and faulted dykes, a funnel-shaped mass of horizontally bedded brown sand containing in places from 10 to 15 per cent. of cassiterite. As this bedded material occurs in a hollow surrounded by quartz-porphyry Mt. Bischoff was regarded as a volcano, with the crater filled by the sands of the "Brown Face." Some concretions of carbonate of iron were regarded as water-worn pebbles. An adjacent white sand and clay known as the "White Face," was rich in tin derived from broken veins of cassiterite. Examination of the mine in 1904 led me to the conclusion (*Science Progress*, 1906, pp. 126, 127) that these materials were not alluvial, but were due to the settling of quartz grains left as the country was decomposed by pneumatolytic solutions. The Brown Face is a gossan due to the weathering of a mass of tin-bearing pyrites in porphyry and slate. The slate was injected by quartz-porphyry dykes and both rocks were charged with pyrites and cassiterite introduced by boric and fluoric acids,

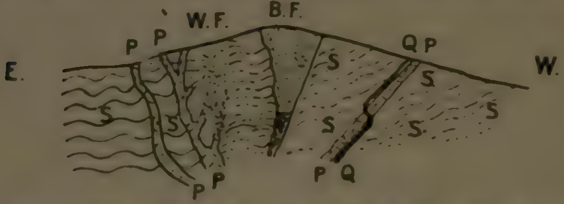

FIG. 26.—SECTION ACROSS THE MOUNT BISCHOFF MINE, TASMANIA. S, slate; P, quartz-porphyry; Q, quartz-vein; W.F., the White Face; B.F., the Brown Face.

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[1] The geology of the mountain was described by Kayser, *Aust. Assoc. Adv. Sci.*, iv, 1892, pp. 352-8. The topaz was recognized by von Groddeck (*Z. d. g. G.*, xxxvi, 1884, p. 643). A later account of the mine has been given by J. G. Weston-Dunn (*Econ. Geol.*, xvii, 1922, pp. 154-93). Pseudo-bedded tin deposits in the Malay Peninsular have also been described by Scrivenor and Jones.

which completely decomposed the silicates, removing the aluminium as fluoride, leaving the silica as grains of quartz, and etching the quartz-phenocrysts of the porphyry. The residual quartz sank as the alumina was removed in solution, and the sand acquired its bedded structure. The White Face consisted of quartz-porphyry, which was altered into concretionary and radial growths of topaz during the introduction of the cassiterite; its residue, owing to the absence of pyrites, is a white clay, which includes prosopite (CaF_2, $2Al(F, OH)_3$) due to the decomposition of topaz. The pseudo-sedimentary nature of the residual deposits of Mt. Bischoff has been fully described by H. Herman (*Proc. Austral. I.M.E.*, 1914, p. 301).

Lodes of quartz with coarse cassiterite occur at Mt. Bischoff, but have been of secondary importance.

GERMANY, MALAYSIA, AND NIGERIA—The German tin-field at Zinnwald includes a "stockwork" or impregnation of thin veins along the upper part of a granite intrusion; its cassiterite is associated with topaz and tourmaline, and is doubtless due to pneumatolytic solutions which spread through the crust of granite instead of forming a deep lode as at Dolcoath or large ore-body as at Mt. Bischoff.

In recent years the largest supplies of tin have come from the Malay States, which with Siam, Southern Burma, and the islands of Billiton and Banka, yielded in 1925 60 per cent. of the world's supply. The tin-fields consist of granite, in places injected into schist and limestone. The tin is associated with tourmaline and was introduced by pneumatolysis. It occurs in thin veins, which are often crowded as a stockwork. The tin, however, rarely pays to work except where it has been concentrated by river action into alluvial placers, some of which are below sea-level, or by settlement *in situ* from decomposed and partially removed country rock. Some of the deposits are pseudo-bedded like the Brown Face of Mt. Bischoff. In some places, as at Kinta, the tin has been left *in situ* by the decay of altered schist and solution of limestone (W. R. Jones, *Q.J.G.S.*, lxxii, 1917, p. 177). One lode, the Lahat Pipe, in limestone, was worked to the depth of 314 feet. Some pegmatite veins contain nodules of cassiterite (Cameron, *Ming. Mag.*, xxxi, 1923, p. 276).

Many of the detrital tin deposits are worked by hydraulic sluicing (cf. p. 53) at costs as low as 3d. per cubic yard (W. R. Jones, *Tin Fields*, 1925, p. 179).

The tin mines of Nigeria work alluvial deposits derived from intrusive granites. The fields are on and near the plateau of Bauchi, S. of the famous city of Kano. The tin has long been worked; it may have supplied some of the metal for the ancient bronzes of Benin. Tin was smelted by workers from Kano who cast it into impressions of straw, and sold it in 9-inch lengths weighing 66 to the lb. (*G.S. Nig., Bull.* 4, 1922, pp. 43-5). The age of the Nigerian tin granite is regarded as pre-Palæozoic. The field is also exceptional by the absence of tourmaline (*ibid.*, p. 41). The ores are nevertheless of pneumatolytic origin, for the adjacent granite has been intensely silicified and impregnated with topaz and often fluor-spar. The Nigerian tin was due to fluoric and not to boric acid.

Bolivia—Bolivia is now one of the chief tin-producing countries, yielding in recent years about 20 per cent. of the total output. The ores have been regarded as different in origin from those of other fields, owing to the reported absence of tourmaline and topaz. The tin-fields trend along the Andes S. of the capital, La Paz. The country is composed largely of Silurian and Devonian slates, which have been invaded by granite and quartz-porphyry, altered by infiltration of silica and crushed into quartz-schists. Vast volcanic eruptions in the Upper Cretaceous and Kainozoic discharged andesites and rhyolites.

The tin deposits are of two types. The first are fissure-lodes and brecciated zones, in which quartz and cassiterite have replaced the country rock. The second type includes the famous silver mines of Potosi; the ores are quartz with complex sulphides of copper, lead, tin, and antimony, with a little cassiterite and tourmaline. The reported absence of tourmaline led A. W. Stelzner (*Z. d. g. G.*, xlix, 1897, pp. 116, 120) to describe the Bolivian tin ores as unique, and as deposited by ordinary mineral springs. According to W. R. Rumbold (*Econ. Geol.*, iv, 1909, pp. 321-64) the ores with the granite and quartz-porphyry are normal and always contain tourmaline; whereas it is rare with the sulphide ores, which he regards as much younger and formed in the volcanic period. Miller and Singewald (*Min. Dep. S.*

Amer., 1919, pp. 94-100), on the other hand, consider that the ores belong to one period which was later than the volcanic eruptions, and so of modern date and moderate depth. W. M. Davy (*Econ. Geol.*, xv, 1920, pp. 463-96) accepts the late Kainozoic origin of both types, but claims that the granite and quartz-porphyry ores were formed under deep-seated conditions, and the tin-silver sulphide ores at moderate depths.

The sulphide deposits are famous for their richness in silver and yield but little tin; their stannite has been even less productive than that of New South Wales. The economically valuable Bolivian tin ores were formed under pneumatolytic conditions like those of other important tin-fields.

TIN-FIELDS IN GENERAL OF PNEUMATOLYTIC ORIGIN—Sulphide tin ores occur at Campiglia in Tuscany at the contact of augite-porphyry with Jurassic limestone. Tin in small quantities occurs in pegmatites in South Carolina and the Black Hills of South Dakota, and in stringers in granite near its contact with limestone in Alaska (Fay, *Tr. Amer. I.M.E.*, xxxviii, 1908, pp. 664-82); and also in quartz lodes containing lumps of coarse cassiterite in the Mt. Cudgewa tin-field in the Mitta-mitta Valley, Victoria (Gregory, *Bull. G.S. Vict.*, 1907, No. 22, p. 107), which, though yielding beautiful museum specimens, were too scattered in barren quartz to be mined profitably.

The essential feature of the chief tin lodes is their formation under deep-seated conditions within or beside intrusive massifs of Upper Palæozoic granites, by the action of boric and fluoric acids with superheated steam. The granite attacked by these pneumatolytic agents has been reconstituted as bands of pegmatite; the felspars have been destroyed, leaving a rock composed of quartz and mica, which is known as greissen and has been described as the parent rock of tin.

The rise of the tin-bearing solutions through the granite mass explains why tin deposits beside small granite intrusions are often richer, as in Burma, than beside large intrusions.

A small outcrop (Fig. 27) may be the tip of a projection from a large granite mass, while a broad outcrop shows that the upper part of the granite has been removed by denudation. As the most concentrated deposition of tin would have been at the upper edge of the granite, most of the ore from a wide outcrop would have been scattered and only the poorer marginal deposits left.

VARIATIONS IN PRICE OF TIN—For many years the normal price of tin ranged a little below £100 a ton; in 1916 it was £162 a ton, in 1920, £423 a ton, and after falling to £139 in 1922, rose in 1926 to over £300 a ton. The price has been subject to sudden fluctuations, and ore deposits that were paying well are for a time rendered worthless. Sensational statements made during a quarrel between two groups of Chicago meat packers led to a fall in the demand for canned meat, and therefore for tinned plate, that closed nearly all the tin mines in Tasmania. The tradespeople at the mines were ruined, owing to a commercial quarrel at their antipodes.

FIG. 27.—RELATION OF THE WIDTH OF GRANITE TO TIN PLACERS.
Relation of the width of granite outcrop to richness of tin placers. The surface at A would bear washings from the tip of the granite which is rich in cassiterite. In the surface at B, the poor lower margin of the granite is exposed and the alluvial tin ore will be less abundant. The cassiterite in the granite represented by black dots.

TUNGSTEN

(W; sp. gr., 19·1; at. wt., 184; melting-point, 3100° F.) The main use of tungsten is for high-speed tool steel, which remains hard and tough to an almost red heat. As the melting-point of tungsten is high and its rate of expansion nearly the same as that of glass and platinum, it is used for electric lamps. It is also useful in dyes, and in colouring glass and porcelain.

SOURCE OF TUNGSTEN—Most of the supply is obtained from wolframite ($(FeMn)WO_4$), which is an iron-manganese tungstate due to the intergrowth of ferberite, iron tungstate, and hubnerite, manganese tungstate. A small supply comes from scheelite, calcium tungstate ($CaWO_4$). Wolframite is mostly found in quartz-veins in granite; it is of pneumatolytic origin and is associated with quartz, tourmaline, topaz, fluorite, and tin. One of the best-known fields is Tavoy in South Burma; wolframite occurs there in schists which during the uplift of the Altaid Mountains at the end of the Palæozoic were intruded by granite and pneumatolytic quartz-veins. According to Morrow Campbell, tin is present in the lower part and wolframite in the upper part of these veins. Wolframite is sometimes mined from the lodes, but most of it is obtained by washing gravel or decomposed country rock; these deposits often yield 3⅛ lb. of wolframite per cubic yard.

Chinese Deposits—Wolframite occurs under similar geological conditions in the province of Kiangsi in Southern China. The ore there was at first obtained from alluvial deposits, but some quartz-lodes in granite are now being mined and also yield some tin. China is now the largest producer of tungsten, and in some recent years has supplied half the world's output. Wolframite occurs in Siam, the Malay Peninsula, and the Chillagoe and Mt. Carbine fields in Queensland. One large deposit of the iron tungstate variety of wolframite occurs in Colorado.

The chief deposits of scheelite are of Kainozoic age and occur in the western mountains of the United States, especially in California; the scheelite occurs with garnet and epidote in limestones altered by granodiorite intrusions.

Wolframite and scheelite both have nearly the same specific gravity as cassiterite; but wolframite is easily separated magnetically, and scheelite, for which this process is not available, does not often occur with tin oxide. The chief supplies of tungsten come from China, Burma, and the United States, the combined yield of Spain and Portugal being fourth in quantity. The output increased from 7800 tons in 1913 to 21,600 tons in 1917. The material is sold according to the percentage of tungstic acid (WO_3); the standard quality contains 65 per cent. of that oxide; the price has usually varied between 25s. to 35s. per unit, though during the War the output rose to over 30,000 tons in the year and the price to 60s. per unit (or nearly £200 per ton); in 1924 the output fell to 5500 tons and the price to as low as 9s. 6d. per unit.

CHAPTER VI

ORES OF COPPER

Copper—Qualities, Uses, and Price—Copper (Cu, named after Cyprus; at. wt., 63·5; sp. gr., 8·9; melting-point, 1950° F.), the red metal, was one of the metals most used by prehistoric man, for native copper is widely distributed, easily wrought, and bronze, its alloy with tin, makes excellent tools. Copper being soft, malleable, ductile, and tough, can be hammered into sheets, drawn into strong thin wire, and beaten into cooking pots and water vessels; it is used for electric cables as it is the best conductor of electricity, and is the main constituent of bronze and brass. It does not readily rust, but the surface slowly alters into green carbonate, which gives a pleasing colour to copper sheathing on roofs.

Copper is found in many altered basic igneous rocks, and silicate of copper is possibly a primary constituent of some ferro-magnesian minerals. The primary ores are chiefly sulphides, usually combined with iron, as in chalcopyrite ($CuFeS_2$, 34·5 per cent. copper) and bornite (Cu_3FeS_3 with 55·5 per cent. copper); the secondary ores include chalcocite (Cu_2S, 29·8 per cent. copper) and cuprite (CuO, 88·8 per cent. copper). Most copper ores are easily dissolved and their constituents separately deposited; chalcocite is often thus formed in secondary enrichments, though it is sometimes primary, as at Butte, Montana, Mt. Lyell in Tasmania, and in Connecticut (Bateman, *Econ. Geol.*, xviii, 1923, p. 122).

British mines, mainly in Cornwall and Devon, from 1821 to 1830 yielded 45 per cent. of the world's copper supply (N. Brown and Turnbull, *Century of Copper*, 1906, p. 6). The British output fell to 30 per cent. after 1840, but was important until 1871. In the last decade it was only ·15 per cent. of the total and is exceeded by that of seventeen other countries.

The price of copper undergoes great variations, which make or mar the fortunes of mining fields. The price of English tough copper (99½ per cent. of copper; standard copper, now generally quoted, has 96 per cent.), was £160 a ton from 1801-10; the price fell to £55 between 1891-1900; it rose to £127 in 1917, but since the War it has again fallen, and early in 1927 was below £55.

The fall in price has been due to the increased output especially from America. In 1801-10 Russia was the second producer with 18 per cent. of the total. Australia, towards the middle of the last century, was the third producer, but its output has fallen by two-thirds. The United States now provides sometimes 75 per cent of the world's output, the rest coming mainly from Chile, Africa (owing to the growing production from Katanga in the Congo basin), Portugal, Peru, and Australasia. The world's production in 1890 was 260,000 tons; the record, 1,415,000 tons, was in 1917 owing to the demands of the War, after which there was a serious decline; the output has again increased to a little over 1,400,000 tons in 1925.

CLASSIFICATION OF ORES

Copper deposits may be divided into four chief groups—primary lodes, replacement ores, secondary enrichments, and sedimentary ores; the classification is difficult and indefinite as the copper minerals, being easily soluble, are liable to concentration by repeated solution and redeposition. Primary and secondary ores often occur in the same mine. The value of many mines depends on the secondary enrichments, the primary ores being of low grade. The copper ores may be classified as follows:—

SECT. A. PRIMARY ORES—

I. *Primary Lodes*—

- (*a*) Pneumatolytic—(1) Svartdal, Norway; Vogtland, Saxony; Rossland; Burra-burra; (2) in volcanic pipe—Braden, Chile.
- (*b*) Quartz-lodes. Cornwall.
- (*c*) Pipe-lodes and shoots. Wallaroo; Namaqualand.

II. *Primary Disseminations and Replacements*—
  - (*a*) Disseminations. Monte Catini.
  - (*b*) Replacements in limestones and tuffs. Chillagoe.
  - (*c*) Replacement—Contact lodes. Tuscany; Oslo (Kristiania).
  - (*d*) Pyritic masses in shattered rock. Rio Tinto; Mt. Lyell; Mt. Morgan; Ducktown; Rammelsberg.

SECT. B. · SECONDARY ORES—

III. *Secondary Enrichments*—
  - (*a*) Chalcocite bodies. Butte.
  - (*b*) Over-disseminations and replacement bodies. Arizona.
  - (*c*) Of sedimentary ores. Katanga.

IV. *Bedded or Sedimentary Ores due to Redeposited Alluvial Ores*—
  - (*a*) Mansfeld; Cheshire. (Also Chile.)
  - (*b*) Redeposited ores in conglomerates and amygdaloids. Michigan.

A. PRIMARY ORES

PNEUMATOLYTIC LODES—ROSSLAND, SOUTH AUSTRALIA, AND BRADEN MINE, CHILE—The two divisions of the primary lodes are due to solutions acting at different temperatures and depths. Pneumatolytic lodes are formed at the higher temperatures and are associated with tourmaline or fluorides. Thus at Svartdal, in Norway, the ore occurs with tourmaline in a granite of which the felspar has been replaced by quartz and mica. Copperopolis in Oregon owes its name to ore with tourmaline in diabase. The ore of Vogtland, in Saxony, was due to fluoric acid and is in thick veins of fluorite with occasional tin.

At Rossland on the southern border of British Columbia (C. W. Drysdale, *G.S. Canada*, Mem. 77, 1915), another lode-type has been formed in a massif of monzonite. The lode minerals include much biotite and a little tourmaline, with copper, gold, and nickel. The lodes are often 25 feet thick, and have in part replaced the walls. The lodes were formed at high temperatures as they are associated with many basic dykes, some of which are earlier and others later than the lodes. The lodes in 1909 had been worked to the depth of over 2000 feet, and the ore contained an average of ·8 per cent. of copper, gold worth about £2 10s. per ton of ore, and some nickel. The ores are clearly of hydrothermal origin, and support the same formation of the nickel ores of Sudbury (cf. pp. 114-18).

The copper mines which saved South Australia at a critical stage of its early history derived their copper from a pneumatolytic source. The rich oxidized ores at Burra-burra, which yielded 22 per cent. of copper, were discovered in 1845, and are in altered slate and limestone. The primary ore was discovered at Moonta in 1861, and is a pegmatitic formation of quartz, microcline, tourmaline, apatite, and fluorite. Five lodes occur in quartz-porphyry, which at Moonta has been intruded by pre-Cambrian granite; the lodes contain 2 to 5 per cent. of copper in chalcopyrite, and were covered by an oxidized zone containing copper carbonates, atacamite (oxychloride of copper), and native copper. The Moonta Mine was once the deepest copper mine in the world and has been worked to 2600 feet.

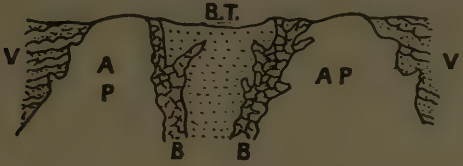

Fig. 28.—The Braden Copper Mine, Chile.

One stage in the development of the Braden Copper Mine, Chile. V, the volcanic rocks forming the country; AP, intrusive andesite-porphyry; BT, Braden tuffs filling the explosion crater; B, the intrusive breccia invading both the porphyry and the tuffs.

The Braden Mine, Chile (Lindgren and Bastin, *Econ. Geol.*, xvii, 1922, pp. 75-99), illustrates the relations of the pneumatolytic to other copper ores (Fig. 28). It is in the Western Cordillera about 100 miles S.E. of Valparaiso. The mine is in an extinct volcano in Kainozoic tuffs and lavas, which have been intruded by an andesite-porphyry that grades into quartz-diorite. This intrusion was fractured and invaded by a superheated boric acid solution which altered the rock into a mosaic of quartz, tourmaline, sericite, and rutile, and deposited large quartz-veins containing sulphides and magnetite. While the andesitic diorite was still charged with superheated water it was invaded by dykes of alkaline dacite-porphyry. The consequent rise of temperature, perhaps combined with release of pressure owing to fracturing, exploded the superheated water and blew out a crater 3000 feet in diameter and 6000 feet deep. This crater was occupied by a lake and gradually filled by the Braden Tuff being washed into it. Solutions rose along fractures around the crater, and deposited quartz-veins with tourmaline and pyrite, and large bodies of ore containing about 1 per cent. of copper. The less permeable tuffs received lower-grade ores with ½ per cent. of copper. An alkaline porphyry breccia was upthrust between the tuffs and the crater wall, and tourmaline was deposited both in this breccia and the Braden Tuff. As the volcanic activity waned, the rising solutions were cooler and did not carry boric acid; they deposited bornite and other sulphides, sulpharsenites, sulphates, carbonates, and tungstates. Later still cooler solutions deposited chalcopyrite and bornite, with quartz and gypsum, which in some of the cavities grew into crystals 10 feet long. After the volcano had become wholly extinct, descending meteoric waters leached the ores from the surface to the depth of 150-300 feet and redeposited the copper as secondary enrichments of chalcocite. The Braden Mine therefore illustrates all stages from pneumatolytic and contact ores to ordinary quartz-pyrite veins and secondary enrichments. This association of the different types is due to volcanic action being local and intense; in most mining fields the subterranean conditions vary less quickly.

LODES OF CORNWALL—Solutions that acted at less depth and at a lower temperature than those that produced the pneumatolytic ores and had silicic acid as the predominant acid, have formed the quartz-copper lodes, which were for long the chief source of copper. The lodes of Cornwall and Devon show a transition downward into pneumatolytic tin ores; they are typical fissure lodes of quartz with copper sulphides and pyrite, but have replaced some of the wall rock. The Cornish copper mines have an extensive literature (cf. J. H. Collins, *W. of England Mining Region*, 1912, pp. xv-xx).

Pipe-lodes—South Australia and South Africa—The Wallaroo Mines, near Moonta in South Australia, are quartz-chalcopyrite lodes in orthoclase-porphyry. The lodes are pre-Palæozoic, as they do not pass up into the overlying Cambrian. The ore forms deep pipe-like shoots, which contain from 3 to 4 per cent. of copper and have been worked to the depth of 2000 feet.

The Namaqualand copper ores of South Africa occur in shallower pipes which have a regular quincuncial arrangement at the intersections of a network of fractures. According to Kuntz (*Tr. G. Soc. S. Afr.*, vii, 1904, p. 70) the pipes occur where parallel joints cross lode-filled fractures; but according to J. H. Ronaldson (*ibid.*, viii, 1906, p. 161), the material in the fractures looks like dykes though it may be altered gneiss. The ores were obviously due to deposition by solutions passing along intersecting fissures.

Disseminations and Replacements—Fissure lodes are often enlarged by the replacement of the walls. In some cases the ore thus deposited so greatly exceeds that in the fissures that the result is a replacement lode.

The simplest replacement ores consist of scattered grains or small patches of copper sulphides, as in the olivine-gabbro of Monte Catini in Tuscany, Cuba, and Turkey. The rock beside the Monte Catini gabbro has been altered to a fractured serpentine which contains veins of copper ore.

The second type is commercially more important, and includes masses of copper ore in limestones, as at Chillagoe in Queensland; the solutions having been neutralized by the limestone, the copper minerals were deposited by its replacement. Analogous ores occur in tuffs at Boundary Creek, British Columbia.

A third group of replacement ores are formed as contact products, chiefly beside intrusions of porphyry and diabase into limestone. They occur on a small scale at Campiglia Marittima in Tuscany, at the contact of diabase with Liassic limestone, and near Oslo in Norway. The most important ores of this type are in the Rocky Mountains, and have given rise to great secondary enrichments.

PYRITIC MASSES—SPAIN AND MT. LYELL—Historically the most famous of copper deposits are great lenticular masses of iron pyrites containing a small percentage of copper in South-western Spain—the Tarshish whence Solomon obtained copper for his temple. Mining was begun there in prehistoric times with stone tools, and continued by the Phœnicians, and the Romans who mined there on a colossal scale. After a prolonged interval, the field was re-opened about 1850. The ore is low in grade; most of the primary ore contains between ·2 and ·8 per cent. of copper, though some ore in the upper parts, probably owing to enrichment, contained 3 per cent. of copper. Much of the ore is used for the manufacture of sulphuric acid, the copper being recovered as a bye-product. The chief mines are near Rio Tinto and Tharsis, N. of the port of Huelva. The mining area is bounded to the N. by pre-Cambrian gneisses, schists, and crystalline limestones, in the Sierra de Aracena, and some Cambrian rocks. The mining fields are in a broad band of slates, shales, and quartzites of Silurian, Devonian, and Lower Carboniferous age. These rocks have been invaded by granites, quartz-porphyries, trachytes, and diabases, and some of them have been crushed and sheared by the Altaid mountain movements, which have given the sedimentary rocks a general strike of E. and W. All the igneous rocks have been regarded as intrusive (as by Vogt, Finlayson, and Edge); but the diabase, as near Zalamea, includes tuffs, agglomerates, and pillow-lavas.

The ore deposits consist of many enormous lenticular or boat-shaped masses of iron pyrites. The ore is sharply separated from the country rock or the two pass into one another; the ore is usually massive, but is in places banded. The transition in places from clean slate or porphyry through rock mixed with pyrites into pure pyrites, and the microscopic evidence support the view that the ore was formed by the gradual replacement of the country. The ore-bodies near the margin in places contain inclusions of rock, which are exceptional in the middle, where the replacement has been complete. The upper part of the ore-body is sometimes richest in copper, which may have been concentrated from higher parts of the lode now destroyed or may be due to primary deposition.

The copper-field is about 80 miles long and includes, according to Finlayson (*Econ. Geol.*, v, 1910, p. 407), thirty-three chief ore-bodies. The South Lode of Rio Tinto and its continuation, the San Dionisio Lode, are together more than 1¼ miles long. La Zarza Lode and its continuation Perrunal are together also 1¼ miles long, and their full length is not yet known. La Rosa and the Sotiel are 1150 and 900 yards long respectively. Most of the ore-bodies are between 250 and 600 yards long. The San Dionisio is 800 feet wide, and most of the larger lodes are between 150 and 500 feet wide. Their depth is small in relation to their thickness. According to Finlayson the depth probably in no case exceeded about 3000 feet, and seldom 1500 feet. Some of the ore-bodies are thicker below, as the upper part of the lenticle is still preserved. The ore-bodies occur in different rocks. According to Finlayson's list four of them are in porphyry; two at the junction of slate and diabase; eleven at that of slate and porphyry, as at Rio Tinto and Calanas; and sixteen are wholly enclosed in sedimentary rocks, such as the Tharsis, Sotiel, and El Tinto (Fig. 29) which are in slate.

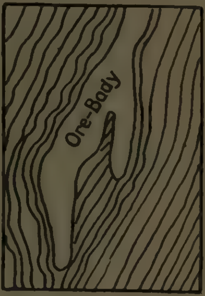

FIG. 29.—ORE-BODY IN SLATE AT THE EL TINTO MINE.

An ore-body in slate at the El Tinto Mine, Santa Rosa, S.W., Spain, after Finlayson. (Cf. Fig. 30.)

MT. LYELL—A similar mass of copper-bearing pyrite occurs at the Mt. Lyell Mine in Western Tasmania, 20 miles inland, N. of Macquarie Harbour. Alluvial gold was found in the district in 1881 and at Mt. Lyell in 1883; in 1891 was found the "Iron Blow," a gossan which contained gold and silver, and covered a large ore-body of pyrite containing sufficient copper to pay for mining, the gold and silver being recovered as bye-products.

The Mt. Lyell Mines[1] occur close to the contact of the

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[1] J. W. Gregory, "The Mt. Lyell Mining Field with other Pyritic Ore Bodies," *Austral. I.M.E.*, 1905, viii, p. 178.

Mt. Lyell schists (porphyrite lavas and volcanic ash which have been crushed into sericite schist), with the massive conglomerates and quartzites of the West Coast Range of Tasmania. The conglomerates are probably Devonian and occur E. of the Mt. Lyell schists, which are thrust over the conglomerate by a long and complex fault, associated with cross-faults and thrustplanes. In places wedges of conglomerate have been thrust into the schists. The Mt. Lyell Mine is in a bay of schist which has been nipped between three faults, and was so shattered that it was completely permeated by ore-bearing solutions. The ore is an irregular boat-shaped mass of iron pyrites which contained over seven million tons. It was at the surface 800 feet long by 200 feet broad; it widened below to 300 feet, but at lower levels decreased in size, and ended abruptly, at the depth of about 750 feet, over the underthrust conglomerate. The ore on the footwall side contained about 2·35 per cent. of copper with a little gold and silver; its richness was probably due to the solutions being nearly stagnant and giving time for the precipitation of the metals. The ore along the hanging wall was so low grade that it only paid to mine as fuel and

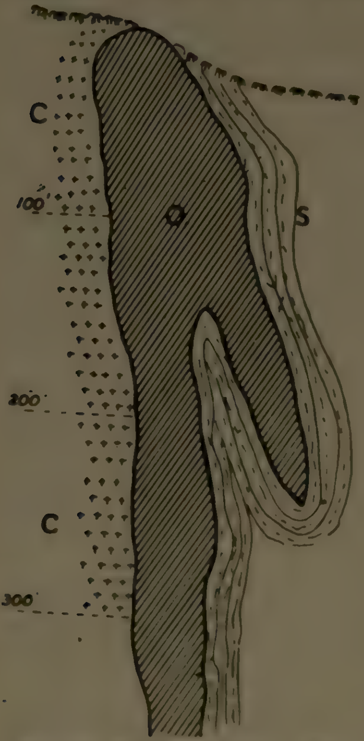

Fig. 30.—The North Lyell Lode.

The upper part of the North Lyell Lode due to replacement of conglomerate and schist along the Mt. Lyell Fault. O, ore-body; C, conglomerate; S, schist.

latterly for the manufacture of sulphuric acid. The pyritic mass contained occasional intergrowths of primary bornite and chalcocite. Most of the pyrites was massive; but in some surfaces in the open-cut the structure of the replaced schist could be seen by a sheen like a watermark. The North Mt. Lyell Mine has a richer quartz-ore containing an average of 6 per cent. of copper in pyrites, bornite, and chalcocite; it is also along the Mt. Lyell Fault (Fig. 30); the upper part is a pipe-lode and in places lies between schist and conglomerate: this pipe rises from a replacement deposit, 100 feet thick and 1500 feet long, which has replaced both rocks. In September, 1925, the ore reserves of the North Mt. Lyell Mine were a little over a million tons containing 6 per cent. copper, 1·33 oz. of silver, and ·015 oz. of gold per ton.

There are four chief theories as to the origin of these pyritic masses. The first regarded them as sediments deposited at the same time as the adjacent rocks (von Roemer, 1873-76; von Groddeck, 1879; Klockmann, 1894, 1902; Bergeat, 1906). Dr. E. D. Peters (1893) adopted this view for Mt. Lyell, regarding the ore as a lake deposit, and it is retained by B. E. Crump in his recent work *Copper* (1925, p. 154). According to the second theory they are fissure-lodes, due to lateral secretion (Collins, 1885), or to ascending solutions (Gonzalo y Tarin, 1888, De Launay, 1889, and Vogt, *Z. prakt. G.*, 1899, pp. 241-54, who regarded them as pneumatolytic after-effects of the porphyry intrusions). A third view explained the ores as contact deposits and was adopted for Mt. Lyell by Daly (*Tr. I.M.M.*, ix, 1901, p. 86) and T. A. Allan, once manager of the Tharsis Mine, but is inconsistent with the occurrence of some of the ore bodies apart from any igneous rock. The alternative theories now held are either that the ores are igneous intrusions (Broughton Edge) or, as suggested by the author in 1904, are due to hydrothermal replacement of rock which had been completely shattered by earth-movements, and saturated by sulphate solutions. Faulting near the contact of quartz-porphyry and shale produced fissures in the quartz-porphyry, while the shale was rendered impermeable by compression.

Hence at Rio Tinto the ore occurs mainly as a replacement of porphyry. Where, as at Mt. Lyell, the rocks in contact are quartzite and slate, the fissuring and replacement were in the slate. This view has been adopted for the Spanish field by J. H. Finlayson (*Econ. Geol.*, v, 1910, pp. 357-72, and 403-37), and Collins (*Tr. I.M.M.*, xxxi, 1922, p. 103); and the Skouriotissa Mine in Cyprus has been explained by C. G. Cullis and A. B. Edge as due to the replacement of pillow-lava (*Ming. Mag.*, xxviii, 1923, p. 342).

The replacement theory is supported by (1) the absence of contact metamorphism or of the baking of the slate; (2) the molecular replacement of porphyry or slate by pyrites, and not of its displacement by a molten intrusion; (3) the frequent gradual passage from rock to ore, as described by Collins and Finlayson, and clearly shown at Rio Tinto; (4) the occurrence of the ore bodies in zones of shearing and faulting, the association with igneous rocks being due to the intrusions having made zones of weakness that were liable to subsequent fracture and impregnation by solutions from below; (5) the presence in the ore of about 3 per cent. of free silica, which would have been converted to iron silicate if the ore had been molten; (6) the presence of such characteristic hydrothermal minerals as sulphides of iron, copper, lead, and zinc, also of gold and silver, quartz and sericite, and the absence of tourmaline, apatite, primary micas, pyroxenes, and iron-silicates, which are the characteristic igneous or pneumatolytic minerals.

Lenticles of similar nature are well known at Rammelsberg in the Harz, at Ducktown in ~~Virginia~~, and in the lower 7l. part of the Mt. Morgan gold mine in Queensland (cf. p. 52).

B. SECONDARY ORES

SECONDARY ENRICHMENTS—(*a*) BUTTE, MONTANA[1]—The solubility of copper salts has led to the segregation of the disseminated primary copper minerals of contact and sedimentary ores. These secondary concentrations are the mainstay of some fields, as at Butte, Montana, which long gave the United States its predominance in copper output. Mining began at Butte in 1864 for alluvial gold; silver was worked from 1865 to 1893, and copper, unsuccessfully, from

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[1] R. H. Sales, *Tr. Amer. I.M.E.*, xlvi, 1911, pp. 3-109.

1872 to 1874. In 1881 Marcus Daly of the Anaconda Silver Mining Co. found rich copper ores below those of silver; the Anaconda Smelter, which began operations in 1884, led to Butte becoming the most prolific copper-field in the world. The mines occur in an Eocene granite rock, a quartz-monzonite, which in the Miocene was invaded by masses of aplite and dykes of quartz-porphyry, and covered by rhyolitic lavas. The monzonite is traversed by three series of lodes. The oldest are quartz-veins which trend E. to W., and contain silver in the northern and copper beneath silver in the southern parts of the field. These lodes were torn by N.W. to S.E. clefts and faults, which are charged with copper ores. The third series trends from N.E. to S.W., cuts across the two earlier series, and contains ore broken from them and some primary ore deposited by solution. The famous Anaconda Lode (Fig. 31) is one of the oldest series, and has been worked for a mile and a half long, and to 2400 feet deep; its width is in places 100 feet, and large sections averaged 40 feet. The upper part of the lode consisted of iron-stained quartz with silver ores; between 200 and 400 feet deep it held oxidized copper ores; and below 400 feet occur large secondary bodies of chalcocite (Cu_2S), which are especially rich where the lode is crossed by faults. The Anaconda Lode is traversed by compound faults, such as the Rarus Fault, which has shattered a band of monzonite in places 130 feet wide; the broken rock is seamed with quartz-veins and impregnated with sulphides.

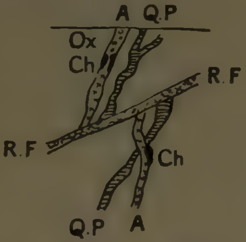

Fig. 31.—The Anaconda Copper Lode.

Butte: the lode is, A, near a quartz-porphyry dyke, Q.P., and is traversed by the complex Rarus Fault, R.F.; OX, the oxidized portion above water-level; Ch, secondary enrichments of chalcocite.

The Butte ore was at one time attributed to lateral secretion; but there seems no reason why some of the lodes should contain silver and others copper if both sets were filled from the same rock. The ores have probably been deposited by solutions which came from the ore-zone beneath the monzonite, and reached the surface through fractures consequent on its intrusion. Some of the lode-fissures were due to shrinkage of the cooling monzonite and dykes. The sulphides in the original lodes were sparse; but as the country was cut down by denudation the primary sulphides were concentrated into bodies of chalcocite which formed the wealth of the Butte Field.

OVER-DISSEMINATED AND REPLACEMENT BODIES—ROCKY MOUNTAINS, CONGO—The copper-fields of the Rocky Mountains, in Arizona and Utah, contain secondary ores concentrated from low-grade primary sulphides. The mining districts consist of ancient granitic rocks covered by Palæozoic and Mesozoic limestones; these rocks were invaded by Lower Kainozoic granite-porphyry and monzonite, beside which are contact bands of lime-silicates, including garnet, tremolite, vesuvianite, diopside, and epidote, and of calcite mixed with chalcopyrite, bornite, and pyrites. Lenticular and tabular deposits of the same ores pass from the porphyry into the limestone, which also contain scattered grains and thin veins of the sulphides. The primary ores contain about 5 per cent. of copper, and mining is dependent on the large secondary enrichments of chalcocite and carbonates. At Bisbee (cf. Ransome, *U.S.G.S.*, *Prof. Pap.*, No. 21, 1905), 6 miles N. of the Mexican frontier, the mines are in Carboniferous Limestone; the ore is oxidized to the depth of 1400 feet, and caves contain the beautiful blue azurites for which the Copper Queen and other mines were famous. At Clifton-Morenci in S.E. Arizona (cf. W. Lindgren, *ibid.*, No. 43, 1905), the granite and monzonite-porphyry intrusions and many dykes are bordered by contact ores; the ores to the depth of from 50 to 200 feet were mainly oxidized; from the depth of 100 to about 400 feet lay secondary enrichments of chalcocite with from 3 to 4 per cent. of copper; below 400 feet are low-grade primary ores of pyrite, chalcopyrite, and blende. The mines at Bingham, in Utah (Butler, *ibid.*, No. 111, 1920, pp. 340-62), in Palæozoic limestones are at the margin of monzonite and diorite-porphyry, and contain masses of chalcocite concentrated from the primary ores.

Most of the vast quantities of low-grade ores of Katanga in the Belgian Congo appear to be also alluvial in origin (as suggested by Lindgren, *Econ. Geol.*, vi, 1911, p. 575; cf.

Ball and Shaler, *ibid.*, ix, 1914, pp. 629-30, 632). They are interstratified with slates and dolomites. The beds in depth contain sulphides. The rich ores are mainly carbonates, especially malachite, and are secondary enrichments containing from 6 to 14 per cent. of copper. The original bedded ores are pre-Palæozoic; the country has been lowered probably thousands of feet by denudation, and ores from the rocks removed have been concentrated in the enrichments.

BEDDED OR SEDIMENTARY ORES — MANSFELD AND MICHIGAN — This group of copper ores has given rise to prolonged difference in interpretation. Red sandstones of different ages and countries are associated with copper ores, which at Mansfeld in Germany have been worked since the year 1199.[1] That field has yielded 800,000 tons of copper and been the second largest copper-producing field in Europe. The area has been described as the birthplace of stratigraphical geology. The ore occurs in a Permian bituminous shale (the Kupferschiefer), which lies above the Lower Permian red sandstones, and below the Zechstein, a Middle Permian limestone.

The average ore contains about 1½ per cent. of copper, and occurs in three layers of a bed which is usually from 20 to 24 inches thick; but the ore may penetrate 4 inches into the underlying sandstone. The bed is often traversed by faults which contain copper and cobalt.

The great extent of the deposit—in the Mansfeld syncline alone it is 15 miles wide—suggested the origin of the copper by precipitation from the Permian sea. The bed contains land plants and fossil fish of which the distorted shape, according to von Groddeck, was due to the agonies of copper poisoning, but was probably caused by ordinary post-mortem shrinkage. According to the second theory, mainly supported by Beyschlag and Krusch, the copper was brought in solution up the faults and precipitated in the shale by its organic matter. The copper is present as grains and nests of chalcocite which is usually, and bornite, which is often, secondary, and as later veins of chalcopyrite; the ore has partly

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[1] For the history of this field, cf. Dr. W. Hoffmann, *Mansfeld, Gedenkschrift zum* 725 *Jaehrigen Bestehen des Mansfeld-Konzerns*, 1200-1925, 189 pp., Berlin, 1925. A recent description of the geology is given by P. D. Trask, *Econ. Geol.*, xx, 1925, pp. 746-61.

replaced the shale, and has mineralized the underlying sandstone and occurs in the faults which are probably Kainozoic. Hence the ore has clearly been deposited or redeposited after the formation of the shale. Beyschlag attributed the source of the ore to the underlying lavas; but they contain no copper and the ore does not appear due to extraneous solutions. Bedded copper ore is generally associated with red sandstones laid down under arid conditions; and the Mansfeld ore may be due to alluvial grains derived from the Harz Mountains and washed into the sandstones, and there dissolved and redeposited in the shale.

The ores in the Triassic sandstones of Alderley Edge in Cheshire[1] are probably also derived from detrital grains. The ore is sandstone with the grains cemented by carbonates of copper and lead. The patches of ore often rest on clay; they may pass gradually into the sandstone or be sharply separated from it. Some of the ore lies in faults, which it entered from the sandstone. There is no evidence that the copper was introduced from fissures. The ore was probably due to the solution of alluvial grains scattered in the sandstones and their redeposition where the solution was kept stagnant by underlying clay. This field between 1857 and 1877 yielded 158,000 tons of ore with an average of 2·1 per cent. of copper, which is similar to the usual grade at Mansfeld.

The copper fields of Michigan, on the southern side of Lake Superior, are in pre-Palæozoic sandstones and conglomerates interbedded with diabase lavas and volcanic ash belonging to the Keweenawan System, which is equivalent to the British Torridonian. The copper is mostly native. In places it acts as a cement to the pebbles, replacing the matrix of the conglomerate and sometimes the pebbles and boulders also.[2] In the volcanic rocks it fills vesicular cavities and fissures, and is often associated with zeolites. The ore forms shoots of which the most important, the Calumet and

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[1] Cf. Dewey, *Geol. Surv. Gt. Brit., Spec. Rep. Min. Res.*, xxx, 1925, who, p. 15, adopts the alluvial origin of the ores.

[2] The replacement nature of the ore was early suggested by Pumpelly, *Proc. Amer. Acad.*, xiii, 1877, p. 253; for the geology of the field cf. R. D. Irving, *U.S.G.S. Mon.*, No. 5, 1883; A. C. Lane, *Michigan G.S. Publ.* 6, 1911, for formation of the ores, vol. i, pp. 41·4.

Hecla Shoot, is in conglomerate; it is about 3 miles long, and varies from 12 to 15 feet thick, and has been mined to the depth of over 6000 feet. The ore is low grade, and has paid to work to a value of ·55 per cent. of copper, for the vein stuffs are brittle and cheaply crushed by stamps, and the metallic copper is separated by simple washing. The copper was at one time considered to have been a primary constituent of the ferro-magnesian minerals in the diabase; but the igneous rocks only contain copper where it has been secondarily introduced. The rocks near the ore have been traversed by hot alkaline plutonic water which probably obtained the copper by the solution of detrital grains in the sandstones. The channels form the shoots, some of which enter the lavas; the reduction of the solution by oxidation of ferrous iron in the diabase or of some ferrous mineral in the conglomerate led to the deposition of the native copper.

CHAPTER VII

ORES OF LEAD, ZINC, AND SILVER

Lead—Its Uses, etc.—Lead (Pb; at. wt., common lead, 207, uranium lead, 206; sp. gr., common lead, 11·33, uranium lead, 11·27; melting-point, 620° F.) is one of the six metals that was used by prehistoric man; it is easy to work, being soft, ductile, and malleable. Among its valuable properties are its flow under pressure while cold, melting at a low temperature, and insolubility in concentrated sulphuric and hydrochloric acids. It is a constituent of some alloys including pewter, and being the heaviest of common metals is used for bullets. In 1925 40 per cent. of the supply was used by the electrical industry and 25 per cent. for paints. British lead mining was at its zenith in 1856 with 353 mines at work, and an output of 73,129 tons of lead and 61,400 oz. of silver. The price of lead was then £32 a ton. The price fell, after the opening of lead mines in the United States, Mexico, and Australia, to as low as £13 16s. per ton in 1896. The United States has in recent years supplied 40 per cent., Mexico 11 per cent., Spain 10 per cent., and Australia 10 per cent. of the world's output. The British Isles in 1924 produced only 10,863 tons, mainly from eight mines. The declining yield of the six chief mining fields has led to the price rising to £40 per ton in 1924, but it has fallen again to £28 in 1927. Native lead is rare, as it is slowly oxidized, but it has been often recorded from torn shot found in gravels. The chief lead mineral is galena (PbS), which is usually associated with blende (ZnS), and nearly always contains silver as argentite (Ag_2S).

Classification of Ores—The primary lodes occur along faults and fractures. Those due to the filling of fissures are often well crustified. Many lodes that are productive in sandstone are barren in slate, which being softer may be crushed and not form an open fissure; the conditions are reversed where the sandstone resisted fracture, and the slate is fissured. In some fields, as at Przibram in Czecho-Slovakia, the lodes are productive both in sandstone and slate. The usual veinstones are quartz, calcite, barite, and fluorite. Fluorite often occurs only in the upper levels, as superheated steam prevents its formation. The pneumatolytic minerals tourmaline and cassiterite are exceptional; but boric acid has in places formed axinite. The deep-seated origin of the primary lodes is shown by their lead being of a higher atomic weight and specific gravity than the uranium lead of igneous rocks.

Primary and secondary lead ores are often closely associated. In secondary ores the zinc and lead are usually separated owing to their different solubilities. The secondary ores are often banded or radial with large crystals, whereas those in primary deposits are usually small and granular. The primary lodes often go deep; they have been worked, for example, down to 1900 feet in the Isle of Man, to 1800 feet in Cornwall, to 1700 feet in Shropshire, to 1800 feet at Wanlockhead, to 2500 feet at the Cœur d'Alene in Idaho, to 3000 feet in Clausthal, and to 3600 feet at Przibram. The lodes are usually a few feet thick, but are often widened by replacement of the walls. Igneous rocks are absent from most lead-fields, and if present, they appear to have had no influence on the mineralization; in Derbyshire they are known as toadstone, a corruption of the German todstein or deadstone, which indicates their barrenness and even unfavourable effect on the lodes.

Primary lead lodes are mostly of medium geological age. They have been formed at lower temperatures and nearer the surface than lodes of copper and tin, but deeper than ores of mercury. Lead lodes occur in pre-Palæozoic rocks, at Broken Hill in Australia, the Northampton field in Western Australia, Northern Rhodesia, British Columbia, Eastern Canada, the Eastern United States, and in Scotland; but the lodes may be much younger than the country rock. Some of the ores are associated with Kainozoic volcanic activity, as at Hauraki in New Zealand. The great majority of primary lead ores were formed during the mountain-movements of the Upper Carboniferous and Lower Permian, e.g. most of the British, German, and Mediterranean ores; but those of Leadville and most other fields in the Rocky Mountains and the Andes are Eocene.

The lead ores may be classified as follows:—

A. PRIMARY ORES—

I. Fissure lodes: Freiberg; Pennines; Leadhills, etc., Comstock, Nevada; Cœur d'Alene, Idaho; Linares, Spain.

II. Replacement Ore-Bodies—
  (*a*) Massive primary ore-bodies: Bawdwin, Burma; Broken Hill; Rhodesian Broken Hill; Sullivan, British Columbia.
  (*b*) Ores with igneous rocks:—
    1. Contact ores beside plutonic masses: South Hill, Idaho.
    2. Ores associated with quartz-porphyry sheets: Leadville, Magdalena, Kelantan, etc.

B. SECONDARY ORES—

III. (*a*) Disseminations: Missouri.
  (*b*) Flats and ore bodies due to descending solutions: Missouri; Silesia; Aachen; Rhodesia.

IV. Sedimentary ores: Commern; St. Sebastian, Gard; Mendip Hills.

SECTION A. PRIMARY ORES

FISSURE LODES—GERMANY, BRITAIN, SPAIN, COMSTOCK—The primary lodes depend mainly on the nature of the country rocks. The classical primary lead lodes are at Freiberg in Saxony, where mining was begun by refugees from Central Germany in the tenth century. The mining field is in the Erzgebirge or Ore-Mountains of Saxony in a dome-shaped uplift of gneiss, on which rest fossiliferous Cambrian rocks. The uplift produced an intersecting network of fissures, with more than 1100 lodes. They are classified into four chief groups, which were formed at two dates. The older series includes three groups: (1) the Noble-Lead lodes with 340 veins, are in two series trending at right-angles, one to

N.N.E. and the other to W.N.W.; they contain quartz and carbonates, galena, and silver ore; (2) the Noble-Quartz veins are rich in silver, especially argentite (Ag_2S), and trend some to N.N.E. and others to E.N.E.; (3) the Pyritic-Lead veins contain quartz, galena and blende, and some copper ores; they generally trend to N.N.E. or N.E. The younger lodes include the Barytic-Lead veins, and were formed in fissures at a lower temperature than the others; they trend W.N.W.; their constituents, galena, blende, pyrite, quartz, fluorite, and barite, show extreme crustification, as in the often-quoted Three Princes Lode. The deep-seated origin of the Freiberg lodes is indicated by the ores of uranium and radium. The lodes were formed during the earth-movements near the end of the Palæozoic. The occurrence of these four different groups of lodes in the same country rock is an argument against the formation of ores by lateral secretion.

The lead and zinc mines of Clausthal in the Harz Mountains of Central Germany were worked even earlier than those of Freiberg. The field is in a fractured belt of Devonian and Lower Carboniferous rocks broken by Hercynian faults.[1] Most of the lodes trend to W.N.W., and are connected by cross-lodes at regular angles, so that the field is cut by intersecting fissures into rhomboids. The richest ore-bodies are where fissures intersect. The lodes have often a sharp foot-wall, but may pass gradually into the country on the hanging wall. They have been worked to the depth of 3000 feet.

The British lead mines [2] include various types of primary lodes. They are mostly in the Ordovician and Carboniferous rocks. The lodes in the Carboniferous Limestone of the Pennine Range, at intervals from Derbyshire to Northumberland, occur along steeply inclined faults, whence horizontal "flats" pass off along the more permeable beds. The flats are replacement bodies, and if connected with the fissures their ores are rich in zinc, which in the lodes increases in depth. A lode is often rich in limestone, and becomes thin and poor in shale or igneous rock, and remakes if it re-enter

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[1] They are regarded as Miocene by von Koenen, *Jahrb. preuss, geol. Landesanst.*, xiv, 1894, pp. 79, 81. The Hercynian age is supported by F. Hornung, *Z.d.g.G.*, lvii, 1905, p. 303.

[2] *G.S. Gt. Brit., Spec. Rep. Min. Res.*, Nos. 17, 19-23, 25-6.

limestone. The ores in the field of Alston Moor are mainly in a zone about 600 feet thick; in Derbyshire they are worked to the depth of 1100 feet, and many of the upper veins are rich in fluorite.

The primary lodes in Flintshire are along fault fissures in Carboniferous Limestone, and trend from N.W. to S.E.; they contain galena, blende, and about 15 oz. of silver to the ton. Some cross-courses contain secondary ore which contains no zinc, and is poor in silver. In the Isle of Man the Laxey Lode has been worked through the Carboniferous Limestone into slate and granite, to the depth of 1900 feet.

The lead lodes in the Ordovician sandstones, grits, and graywackes are often more regular than those in limestone, as the fractures are simple and straight. The lodes of Leadhills and Wanlockhead in Scotland (J. Mitchell, *Ming. Mag.*, xxi, 1919, pp. 10-20) are confined to the Lowther Grits, as the fissures in the slates were closed by the collapse of the walls. The lodes are usually about 2 feet thick, but widen up to 18 feet. The ore is usually in shoots. The first-formed minerals in the primary ore are quartz, dolomite, and calcite; next pyrites and chalcopyrite; subsequently galena and blende. A second mineralization produced much larger crystals. Finally surface waters formed the rare minerals for which the gossan and oxidized ore of these mines are famous. The age of the ore formation has been attributed to the Caledonian; but the parallelism of the lodes to the faults in the Hamilton and Sanquhar coalfields and the partial mineralization of some Lower Devonian felsite dykes indicate their Permian age.

The Shropshire lead-field at Shelve and Snailbeach was worked by the Romans, and has been mined to the depth of 1650 feet; the lodes are in the sandstones of an anticline, and are unproductive in the shales. Barite is the chief veinstone in the upper part; the proportion of zinc to galena increases with depth.

The lodes in Central Wales lie along faults in Ordovician slates and mudstones; they contain much brecciated rock and the walls are strongly slicken-sided. The lodes extend for miles trending E.N.E. with ore-shoots at intervals. Much of the ore is found along secondary fractures, some of which are horizontal flats. The lead ores in Cornwall and

Devon generally occur in the Devonian slate or killas, as cross-courses through the copper lodes; they have been worked to the depth of 1800 feet; the ores were deposited after the tin and copper.

The Spanish lead mines were opened by the Phœnicians and were worked by the Romans to the depth of 600 feet. The Linares field, 160 miles S. of Madrid, was from 1870 to 1910 the most prolific lead-field in the world. Its mines are of great variety; they are mainly vertical lodes trending W.S.W parallel to the great Guadalquivir fault—a conspicuous feature in the geology of Southern Spain. The Arroyanes Lode consists of several parallel veins along faults in granite; it is 5 miles long, usually 3 feet thick, and has been worked to the depth of 1300 feet. Further N. is the Guindos line along fractures in Silurian and Ordovician rocks; the lodes are productive in quartzite, but are closed when the lode track crosses slate. The lodes were formed slowly, for one generation of veins was fractured and displaced, before a second set was deposited.

Further N. in the Sierra Morena is the Centenillo Mine, which was also worked by the Romans; one of its lodes, the Mirador, is a sheet of pug, which has to be valued by sampling as the galena is invisible; it is a Hercynian lode that was ground to powder by Alpine faulting. The leaching of the ore is indicated by the absence of zinc.

The age of the Linares system is probably Hercynian, as the local Triassic conglomerates contain fragments of the ore and lode-quartz. A little ore extends into the Trias by secondary migration.

The Comstock Lode in Nevada is one of the most famous and richest in mining history (Becker, *U.S.G.S.*, Mon. 3, 1882). Alluvial gold was worked in the field for years before the discovery in 1859 of its silver-lead ores. The German physiographer, von Richthofen, described the lode as a contact formation in a long series of igneous rocks, which he regarded as lavas, each characteristic of a separate age. They are now regarded as variously altered andesites (*U.S.G.S.*, *Bull.* 17, 1885), and the lode as formed along a fault up which rose superheated water that altered the andesite into propylite. At one time the lode was attributed to lateral secretion by water percolating through the adjacent rocks, dissolving metals from them, and depositing them in the fault fissure in irregularly distributed rich bodies known as Bonanzas. The deep-seated origin of the ore is however probable from the abnormally high temperature, which rises in the mine 1° F. for every 33 feet of descent. The lode has been worked to a depth of 3000 feet despite the difficulties due to the heat and disastrous irruptions of boiling alkaline waters.

The lead lodes at Aspen in Colorado were formed along fractures in shale, and that at Cœur d'Alene in Idaho in a band of quartzite crushed between faults.

II. Replacement Ore-Bodies

(*a*) Massive Primary Ore-bodies—Burma—Primary fissure lodes and replacement bodies of lead ore often occur together. The Bawdwin Mines in Burma work extensive lead, zinc, and silver deposits (Coggin Brown, *Rec. G.S. India*, xlvii, 1917), of which the outcrops were mined by the Chinese. The ores are in a dome-shaped sheet of pre-Palæozoic rhyolitic tuffs underlain by granite. This dome of tuffs has been broken through by compound faults, which form shear-zones up to 500 feet in width. Some thin persistent lodes have been formed on the faults; the Burman Lode is usually 2 feet in thickness, and its ores, according to Coggin Brown, yield from 15 to 37 per cent. of lead, 13 to 27 per cent. of zinc, and from 9 to 41 oz. to the ton of silver. The Shan Lode is a similar parallel lode in which the appearance of chalcopyrite on the 300 feet level indicates the probability of more copper at a greater depth. In the 500 feet shear-zone the rocks have been faulted and so altered that their volcanic origin is only recognizable in microscopic sections; in this zone an enormous replacement deposit, the Chinaman ore-body, reaches 100 feet in width. It was formed, like the pyritic masses (p. 86), by the replacement of a completely shattered block of country rock.

(*b*) Ores with Igneous Rocks—Contact Ores—Lead ores formed by direct contact are uncommon as they are driven from positions of high temperature; but some deep-seated contact ores beside granite masses are known as at South Hill, Idaho.

Ores with Quartz-Porphyry Sheets—Leadville—Important deposits of lead ores occur with sheets of quartz-porphyry but too remote from it to be contact ores. The leading example is Leadville in the Rocky Mountains in Colorado. The field (Fig. 32) consists of pre-Palæozoic granite covered by Cambrian quartzite, the Ordovician or White Limestone, Devonian quartzite, and the Carboniferous or Blue Limestone; this series has been invaded by sheets of Eocene quartz-porpyhry. After its intrusion the rocks were folded and greatly faulted, and large lenses and sheets of lead and zinc ores formed by replacement in the limestones and mainly in the Carboniferous. The ores were carbonates near the outcrop, and passed below into sulphides.

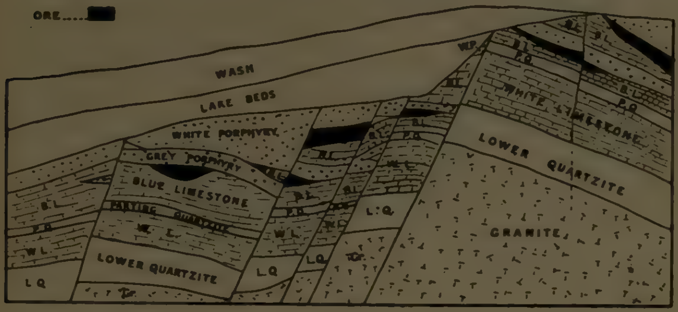

FIG. 32.—THE MINING FIELD OF LEADVILLE, COLORADO.

Section across part of the mining field of Leadville, Colorado (after Emmons and Irving). Porphyry (W.P.) Lower Kainozoic; Blue Limestone, B.L., Carboniferous; Parting Quartzite, P.Q., Devonian; White Limestone, W.L., Silurian; Lower Quartzite, L.Q., Cambrian; Granite, Gr., pre-Palæozoic; the ore-bodies solid black.

The Leadville field was discovered in 1860, and worked till 1874 for alluvial gold. The lead-silver ores were found during 1874 and 1877, when the first smelter was established. The ores used were secondary carbonates in which the silver was enriched to the grade of often 60 oz. to the ton. Emmons (*U.S.G.S.*, Mon. No. 12, 1886) regarded the ores as leached from the porphyry and overlying rocks by descending solutions, and were therefore not expected to go deep or the field to have a long life. Better hopes were given in 1890 by A. A. Blow (*Tr. Amer. I.M.E.*, xviii, 1890, pp. 145-81), who concluded that the ores had risen up the faults. That view has been supported by the discovery (G. M. Butler, *Econ. Geol.*, vii, 1912, p. 318) of the Louemma Vein (Fig. 33), along a fault which passes down from the limestone and porphyry through quartzite into the underlying granite; it is a primary ore containing 8 oz. per ton of gold, 27 oz. per ton of silver, 11·1 per cent. of zinc, and 29·5 per cent. of lead.

The Leadville ores have been followed to depths of 1500 feet and have been traced far from the outcrop. Emmons and Irving (*U.S.G.S.*, *Bull.* No. 320, 1907)[1] showed that the ores extend beneath the Devonian quartzite, where they are away from the porphyry. Nevertheless the ore-bodies in general follow the distribution of the porphyry. Those isolated in the Ordovician limestone may be near some undiscovered intrusion or due to solutions which rose along the course of the porphyry. The Leadville ores do not contain the lime silicates found in contact deposits and the country has been affected by the hydrothermal changes that happen near dykes and sills.

FIG. 33.—THE LOUEMMA VEIN, LEADVILLE.

The Louemma Vein, Leadville (after G. M. Butler). VV, ore vein: Gr, granite; Q, Cambrian quartzite; W.L. Silurian limestone; P, Porphyry.

Deposits analogous to those of Leadville occur in the Magdalena field in New Mexico (*U.S.G.S.*, *Prof. Pap.* 68, 1910, pp. 51-6), and are associated with quartz-porphyry and granite-porphyry. Lead ores beside quartz-porphyry intrusions also occur in Kelantan in the Malay Peninsula.

BROKEN HILL—The Broken Hill mining field in the arid plains of Western New South Wales is notable for its special geological features, its effect on metal prices and on metallurgy and the many mineral species first found in its gossan. The main lode is 3 miles long, in places 200 feet in width, and has

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[1] For results from later mining, cf. G. F. Loughlin, *U.S.G.S.*, *Bull.* 779, 1920.

been worked to a depth of 1800 feet. It was capped by an iron gossan which stood as a ridge above the plains, and was "pegged" out as a tin lode. A shaft was sunk and instead of tin found rich deposits of silver. The arid nature of the country had led to secondary enrichments so large that their yield caused a serious fall in the price of silver. The upper part of the lode was famous for its beautiful minerals, and its many new species of iodides, bromides, and chlorides, which survived owing to the arid climate. The treatment of the ore was troublesome, and led to the invention of the flotation process to separate the rhodonite and blende, which are of the same specific gravity.

The lode is in pre-Palæozoic gneiss and schists, which contain sillimanite and abundant garnets that are earlier than the ores. A bulge on the side of the lode and some secondary arches of quartz led to its description as a saddle-lode (E. F. Pittman, 1892; J. B. Jacquet, *Mem. G.S.N.S.W.*, No. 5, 1894, and Beck, *Rec. G.S.N.S.W.*, vii, 1900, p. 27). The footwall has vast slicken-sided surfaces, and the author in 1904 (*Melbourne Argus*, and *Science Progress*, 1906, p. 131) explained the formation as a fault lode enlarged by metasomatic action at the shallow depth indicated by the abundant fluorite. The lode is a steeply inclined sheet which tapers downwards. This view has been demonstrated in the monograph on the field by C. W. Andrews (*Mem. G.S.N.S.W.*, *Geol.*, No. 8, 1922), who has shown that the silicates in the lode were formed in connection with the faulting.

SECTION B. SECONDARY ORES

(*a*) DISSEMINATED ORES OF MISSISSIPPI—The Mississippi valley (Fig. 34) contains important lead and zinc ores in Palæozoic limestones free from igneous rocks. The ores have been the subject of long controversy as to whether they were formed by ascending or descending solutions. The field of Joplin in S.W. Missouri is in Carboniferous limestone. The fields in S.E. Missouri consist of pre-Palæozoic rocks covered by representatives of all the systems from the Cambrian to Upper Carboniferous. Its lead and zinc ores are mainly in Cambrian rocks, which include in ascending order, the Lamotte Sandstone, the Bonneterre Dolomite, the Davis Shale, the Potosi Dolomite, and a series of sandstones and shales which pass up into the Ordovician. The Bonneterre and Potosi Dolomites contain most of the ores. The rocks have been greatly faulted, but show no evidence of the action of hot waters or high temperatures.

The ores were at first attributed to solutions rising up fault planes. This view was modified by Foster Bain, who, although accepting the primary introduction of the metals by ascending solutions, explained the ores as secondary and concentrated by descending water. The evidence for the descending water is convincing. The ore in the weathered zone of Potosi Limestone is in vertical channels and pipes, which are richest near the surface, and some ore was deposited in cavities as stalactites. The galena is associated with pyrites, barite, blende, smithsonite, anglesite, cerussite, and calcite. The barite of this field supplies a large part of that worked in the United States. The amount of zinc is small. The ores in the Bonneterre Dolomite were also concentrated by descending solutions, and the mines first worked shallow deposits in cavities, caverns, and veins. The ore in the upper workings was mostly the carbonate, cerussite, and coarsely crystalline galena; the deeper galena is in widely disseminated particles. The ore is in places collected in veins, which cut steeply across the bedding; the disseminated ores occur along the upper and lower sides of a band of shale, and in carbonaceous or bituminous layers, and in seams of limestone between shales.

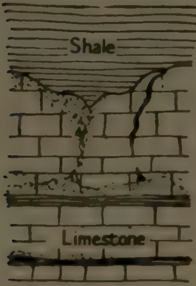

FIG. 34.—LEAD AND ZINC ORES OF MISSOURI.

Diagram of the lead and zinc ores of Missouri (after Buckley). The rocks consist of limestone and shale with the ore deposits descending sometimes in funnel-shaped concentrations and spreading out over the upper side of the bands of shale. Some veins of solid ore.

The condition and distribution of the ore shows that it was formed by descending solutions concentrating scattered ore particles (A. Winslow, *Missouri G.S.*, vii, pt. 2, 1894, pp. 477-87). The process was most active in the Carboniferous, but is still going on (Winslow, *ibid.*, p. 487); and C. E. Siebenthal has shown (*U.S.G.S.*, *Bull.* 606, 1915, pp. 124, 125, 128-9, 131-3) that the well waters of Missouri contain lead, zinc, and copper. The distribution of the ore was determined by the descending solutions. Where the Potosi Dolomite has been exposed by removal of the Davis Shale the ore is in compact shallow deposits; where the dolomite was covered by shale the galena is dispersed in fissures and over the surface of beds of shale.

Buckley holds that instead of the lead having originally come up fault planes, it was scattered sparsely through the pre-Palæozoic rocks of the St. Francois Mountains, which formed islands in the Cambrian Sea. Analyses record ·002 per cent. of lead and ·002 per cent. of zinc in the granite; ·005 per cent. of lead and ·017 per cent. of zinc in the Archean rhyolite; and ·006 per cent. of lead and ·015 per cent. of zinc in the diabase. Buckley calculated that ·002 per cent. of lead in the Archean rocks would amount to 68,000 short tons per square mile for every 1400 feet in thickness. The lead would have been carried to the sea and deposited in the Palæozoic rocks; during their denudation the scattered particles would have been dissolved and carried into the limestones, and there concentrated and precipitated as the ore. The low proportion of zinc in the ores is probably due to the greater solubility of its salts.

(*b*) "FLATS" AND ORE-BODIES DUE TO DESCENDING SOLUTIONS—Some bodies of lead ores are due to replacement by descending solutions, as in the deeper parts of synclinal troughs in the Muschelkalk (Middle Trias) of Silesia, and the lead ores in the Devonian and Carboniferous Limestone of Aachen, which were apparently formed during the Hercynian movements and enlarged during the Alpine movements. The shallow ore-bodies in the Mendip Hills are doubtless also of secondary origin; they occur as irregular lenticles of galena in the upper part of the Carboniferous Limestone, and similar zinc ores occur in the adjacent Permian Dolomitic Conglomerate. The two metals have apparently been separated as they were carried down from former lead-zinc deposits above the present surface.

The pre-Palæozoic ore deposits of Northern Rhodesia include at the Rhodesian Broken Hill Mine a large body of complex lead-zinc ore deposited at the intersection of two fissures traversing dolomite and dolomitic schists.[1] There are no adjacent igneous rocks, and the ore must be due to solutions rising from below; like many pre-Palæozoic ores their composition is varied, including lead, zinc, silver, vanadium, arsenic, and phosphorus. The bulk of the ore was deposited by replacement in limestone, and that now being mined is a mass of secondary carbonates, sulphates of lead, and silicate of zinc due to descending solutions. The mine was discovered in 1902, but the difficulties in treating its complex ore and the distance of 1330 miles from its port at Beira delayed development until after 1916. The ores will doubtless pass downward into primary sulphides, which have already been found in bore holes at depths of between 150 and 400 feet.

Sedimentary Ores—Lead minerals being soft and soluble are comparatively rare in alluvial deposits, but bedded ores of sedimentary origin are found at Commern, N. of the Eifel in Western Germany. A bed of white Lower Trias sandstone contains concretions up to a quarter of an inch in diameter, of quartz grains cemented by galena or cerussite; the richer ore yielded 2 per cent. of lead, but was profitably mined as the concretions were easily concentrated. The lead was probably present in small alluvial grains that have been dissolved and redeposited as concretions. A conglomerate with a cement of pyrite and galena in the Upper Trias at St. Sebastian in the Department of Gard in France, probably also obtained its lead from alluvial grains; its galena cement is analogous to the copper cement in the conglomerates of Michigan.

SOURCE OF THE LEAD IN LODES

The lead ores illustrate the independence of lodes of the country rock. In many areas as in Great Britain, the Linares region of Spain, and the Rocky Mountains, the ordinary lodes of lead are strikingly similar in composition and essential features whether they occur in granite, slate, sand-

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[1] S. J. Speak, *Mig. Mag.*, xxi, 1919, pp. 203-9.

stone, or limestone. The ores at Cœur d'Alene in Idaho and Leadville in Colorado, for example, are remarkably alike, in spite of the difference in structure between the two fields. This similarity indicates that the ores are not derived from either the adjacent sedimentary or intrusive rocks, but come from an ore-zone beneath the igneous rocks of the crust. Like the plutonic waters they work their way upward through igneous and sedimentary rocks alike.

ZINC

ZINC (Zn ; at. wt., 65 ; sp. gr., 7·1 ; melting-point, 790° F. ; volatilizing-point, 1520° F.) is a comparatively modern metal in the western world, though it has been long used by the Chinese. The origin of the name is uncertain, but is probably from *zinn*, the Greek for tin. Spelter, the trade name for the metal, was used in Germany and Spain for the alloy pewter. Zinc is bluish-white, brittle when cold, but malleable when hot. Most of it is used for galvanizing iron as a protection against rust; its other chief uses are as white paint, a drug, and in many alloys, such as German silver, which is composed of nickel, zinc, and copper. The price of zinc before the War was generally about £22 a ton ; it rose to £100 a ton in 1915, after which it fell to £52 and early in 1927 was about £30. The bulk of the zinc ores comes, in order of quantity, from Germany, Australia, the United States, Italy, and Spain. The zinc is seldom extracted at the mines, and the largest production of spelter is in the United States, Belgium, and Germany. Belgium was the home of this industry which is now threatened by the electrical processes of zinc extraction. The common ore is blende (or sphalerite, ZnS), which is constantly associated with galena, and most zinc is obtained from lead ores.

FRANKLIN ORES—In the secondary ores lead and zinc are often separated, and the zinc is frequently deposited in concentric layers known as schalenblende. Some secondary ores are of special value as free from lead. Thus at Franklin, New Jersey, a trough-shaped sheet of ore in a pre-Cambrian limestone includes willemite ($ZnSiO_4$), zincite (ZnO), and franklinite (oxide of zinc, iron, and manganese). The origin of this deposit is a vexed question. The absence of lead suggests that the ore is secondary. It has probably been formed by alluvial grains of blende being deposited in limestone, any galena having been separated during the process; the zinc was concentrated and altered to silicate and oxide during the thermal metamorphism of the area.

The Sullivan Mine, near Fort Steele, British Columbia, the greatest zinc mine in Canada, is a huge replacement deposit, in places 240 feet thick, in slate and quartzite.

Silver

Silver (Ag; at. wt., 107·7; sp. gr., 10·5; melting-point, 1850° F.) is a white metal of a beautiful lustre and useful for jewelry, plate, and currency, as it does not oxidize at ordinary temperatures, and is hardened by addition of copper. It is the best conductor of heat and electricity, and is inferior only to gold in malleability. It was mainly used for coinage, and as its abandonment as the legal standard of value by many countries coincided with increased production, its price fell from about 5s. an oz. between 1860 and 1870 to from 2s. to 2s. 6d. from 1900 to 1915. After the War, it rose to 17s. 6d. an oz., but has again fallen in 1927 to 2s. 1d.

Silver is seldom mined independently, and most is obtained from ores of lead, copper, and gold. The chief silver-producing countries are the United States, Mexico, and Canada. Smaller supplies are obtained in Australia, Peru, Chile, Bolivia, Japan, Spain, and Portugal. The primary ore is a sulphide associated with lead and zinc, and as the problems of its ores are those of the metals with which it occurs, no special reference to them is necessary.

Cobalt Field—Silver, however, occurs in some veins which are worked for it alone, or also for cobalt and nickel. The historic mines of this type are in the gneiss of Annaberg and Joachimsthal in Saxony. The most important now are at Cobalt in Ontario;[1] the veins were discovered casually in a railway cutting in 1903 and regarded as ores of copper. In recent years the field has had an output of silver smaller

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[1] W. G. Miller, *Ont. Bur. Mines*, xix, pt. 2, 1913; Miller and C. W. Knight, *Eng. and Min. Journ.*, xcv, 1913, pp. 1129-33; J. M. Bell, *Tr. I.M. and M.*, xxxi, 1922, pp. 304-32, for S. Lorraine; W. H. Collins, *G.S. Canada*, Map 155 A; C. W. Knight, *Ann. Rep. Ont. Dep. Mines*, xxxi, 1922, pp. 321-58, gives summary of the literature. Microscopic study of the Ore, F. N. Guild, *Econ. Geol.*, xii, 1917, pp. 297-353, pls. X-XXV.

only than Potosi in Bolivia and two fields in Mexico. The ores at Cobalt are associated with four pre-Palæozoic series. The lowest, the Keewatin Series, consists mainly of a basic pillow-lava which is associated with cherts, jaspers, and iron ores, which form "the ironstone formation." Above the Keewatin is the Timiskaming Series of conglomerates and quartzites. The third division, the Cobalt, consists of quartzites and conglomerates. The fourth is the Nipissing diabase, a widespread sill which is in places 1000 feet thick.

The veinstones are chiefly calcite and dolomite with quartz, barite, and fluorite. Native silver is associated with numerous silver, cobalt, and nickel sulphides and compounds with arsenic and antimony. The chief minerals present are argentite (Ag_2S), dyscrasite (Ag_6Sb), pyrargyrite (Ag_3SbS_3), smaltite ($CoAs_2$), and cobaltite ($CoAsS$), with many rarer species.

The mines are of three types. The characteristic type, which has yielded 90 per cent. of the silver, is of veins in the lower part of the Cobalt sediments, below the diabase sill. The veins are near the diabase, the greatest distance being 550 feet in some of the Cobalt rocks, and 350 feet in the Keewatin lavas. The second type is that of the Timiskaming Mine, where the diabase is intrusive into the Keewatin and the veins occur in both. The third type, the Keeley Mine in South Lorraine, is in the Keewatin above the diabase, into which the main vein continues though it is there poor in ore.

According to the generally accepted explanation the metals were originally disseminated through the diabase, from which they have been leached either by its own magmatic water or by surface waters which were heated by it. This theory has serious difficulties: (1) the characteristic constituents—silver, cobalt, nickel, arsenic, and antimony—are not apparent in the normal diabase, which shows no signs of leaching or of solution channels; (2) most of the diabase is not accompanied by ore, which is almost confined to one area of 8 square miles; (3) the Cobalt ores resemble those of Saxony where the country is gneiss and not diabase; (4) similar ore at Cobalt occurs in diabase, in the Cobalt sediments, and in the cherts and lavas of the Keewatin; (5) the ore is dependent on the mechanical and not on the chemical effects of the intrusion, for the veins were formed after the diabase had become cold and been fractured. At the Beaver Mine, e.g. the veins are almost in the middle of the diabase sill, so that it must have been solid, and relatively cool throughout. The association of the veins with faults is established throughout the field (cf. Whitman, *California Univ. Public.*, xiii, 1922, pp. 263-5, 299); many of them have a throw of only a few feet, but they formed impermeable sheets, which blocked the drainage, like the crushed bands with the silver veins of Annaberg. The diabase was the toughest rock in the area, and when the country was folded, shearing took place along the margins of the sill producing many small compression fractures, and planes of slipping. The veins at Cobalt, as at Annaberg, in spite of their great richness therefore have a limited range in depth, as the fissures were formed beside horizontal or gently inclined shearing planes, and not as great vertical fractures. Some of the greater faults, such as Cobalt Lake Fault with a throw of 500 feet, must be deep-seated and may have served as channels for solutions from below. They were at first comparatively cool and deposited calcite veins, which filled any fissures whatever their inclination. Subsequently nickel and cobalt sulphides and arsenides were brought from a greater depth and were deposited mainly in the steeper fissures, because the high gas pressure forced the solutions along the most vertical course. New cracks were formed in the old veins, and native silver deposited after the sulphides, arsenides, and antimonides. According to C. R. Van Hise (*J. Can. M.I.*, x, 1907, p. 53), S. F. Emmons (*Types of Ore Dep.*, 1911, p. 151), J. M. Bell (*Econ. Geol.*, xviii, 1923, p. 694), and E. S. Bastin (*Econ. Geol.*, xii, 1917, pp. 225-8), the rich silver ores are secondary. Some authorities hold that the silver was derived from an upward extension of the lodes; but the arguments by W. L. Whitehead (*Econ. Geol.*, xv, 1920, pp. 127-30) against this view appear conclusive. The native silver though secondary in origin, was probably, as urged by E. S. Bastin, introduced by magmatic waters as acid sulphides during the last stage of mineralization. The deep-seated origin of the ores has been maintained by J. B. Tyrrell (*Tr. I.M.E.*, xxxv, 1908, pp. 494-5), and by Spurr (*Eng. and Min. Journ. Press*, cxvi, 1923, pp. 709-12), who describes the lodes as "veindikes."

CHAPTER VIII

ORES OF FIVE MINOR METALS—NICKEL, MERCURY, ANTIMONY, ARSENIC, AND BISMUTH

NICKEL—USES AND PRICE—Nickel (Ni; at. wt., 59; sp. gr., 8·4 to 8·8; melting-point, 2650° F.) is a widely distributed metal which occurs with native iron in the iron meteorites and must form a considerable proportion of the metallic barysphere. Although early used by the Chinese for coins, it was not discovered in Europe until 1751, and remained scarce until the opening of the New Caledonia deposits in 1890, and of the still richer mines at Sudbury in Canada. In 1900 the world's production was 7500 tons; in 1913 Canada produced 21,600 tons, New Caledonia 2700, and Norway 700. During the War the output rose to 40,000 tons, and the price to £200 per ton; but owing to the stocks then accumulated, the output fell in 1921 to 5000 tons; but it had risen to 36,000 tons in 1925, and the price is now about £170 per ton. Nickel is white in colour, hard and ductile, and does not tarnish as it is not readily oxidized. Its main use is in alloys, such as nickel-steel, of which the strength is largely due to its 3 per cent. of nickel. It lowers the cost of metal structures by reducing the necessary weight. It was long used mainly as German-silver, an alloy of nickel, copper, and zinc. Nickel forms 36 per cent. of invar, a metal used for scientific instruments, as it has the lowest known coefficient of expansion. Grains of a native iron-nickel alloy, Awaruite ($FeNi_2$), are found in serpentine in New Zealand.

Nickel has often been regarded from its association with iron in meteorites as formed by direct igneous action. It is chiefly found in sulphides, especially pyrrhotite (magnetic pyrites), in which it is present as pentlandite ((FeNiS);

22 per cent. of Ni); millerite or capillary pyrites (NiS) is well known from its hair-like crystals. Nickel also occurs as an arsenide, and as a hydrous nickel-magnesium silicate, the garnierite of New Caledonia.

SUDBURY — THE GENESIS OF ITS ORES — The most important nickel mining field is around Sudbury in Ontario, 35 miles N. of Lake Huron. The field consists of pre-Palæozoic rocks, including a basin of sediments, 36 miles by 16, surrounded by a ring of igneous rocks, outside which are steeply tilted sedimentary rocks with greenstones and still older igneous rocks and gneisses. The formation may be tabulated as follows:—

Keewenawan Intrusives—

4th Quartz-diorite; 3rd Granite; 2nd Micropegmatite; 1st Gabbro (Norite).[1]

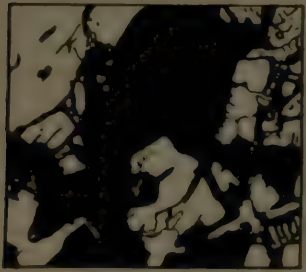

FIG. 35.—NICKEL SULPHIDE ORE OF SUDBURY.

Nickel sulphide ore of Sudbury (after T. C. Phemister). The sulphides, black, are replacing the silicates in "norite." The replacement often follows the cleavage planes in the felspars.

Animikie. Sandstone, slate, and tuff with the Trout Lake Conglomerate at the base.

Greenstone including pillow-lavas like those of the Keewatin, and steeply tilted sediments, conglomerate, and slates which are in places altered to schist.

Granitic gneiss and older schists.

The nickel ores occur chiefly with pyrrhotite and chalcopyrite. Some mines contain sperrylite, the arsenide of platinum ($Pt\ As_2$). The veinstones are quartz, secondary biotite, a felspar-quartz intergrowth, and fragments of the country rocks. The sulphides occur (Fig. 35) as veins

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[1] The traditional name is norite; Prof. Coleman remarked that much of it has no rhombic pyroxene, and according to T. C. Phemister the bulk is gabbro.

cementing broken pieces of the silicates and country rock, or replacing those materials and especially the biotite. According to C. W. Knight, the one fact that may be stated "with certainty is that the sulphides were introduced after the norite-micropegmatite had solidified. This is proved beyond doubt" (C. W. Knight, *Rep. Ontario Nickel Comm.*, 1917, p. 113). The ore bodies form lenticles, pipes, or veins; they are arranged in two groups, one near the margin of the gabbro, and the other in "off-set" bodies away from it. Most interest was at first paid to the marginal ore bodies, and they were explained as due to the heavier magma having sunk to the base forming the gabbro, while the lighter floated up to form the micro-pegmatite, and to the metallic sulphides having collected at the base of the molten gabbro. The off-set bodies were regarded as dykes from the lower part of the gabbro. This origin for the ore was suggested by D. C. Davies in 1883 and by F. D. Adams (*G.S. Canada*, vi, 1893, p. 13), and for the basic rock as well by T. L. Walker (*Q.J.G.S.*, liii, 1897, pp. 52, 56). This theory was authoritatively advocated by Barlow and Coleman. The igneous origin of the ores has been adopted in recent years in a modified form by Tolman and Rogers (*Stanford Univ. Publ.*, 1916), who regard the ores as having been formed later than the gabbro by magmatic solutions, and by Spurr who describes the ores as "veindikes" (*Ore Magmas*, 1923, p. 567); E. Howe (*Econ. Geol.*, ix, 1914, p. 514) and A. M. Bateman (*ibid.*, xix, 1924, pp. 504-20) accepted part of the sulphides as introduced in solution, but consider that part was injected in a molten state.

The igneous theory was early rejected by Posepny (1891), Beck (1901), and by C. W. Dickson in 1903 (*Tr. Amer. I.M.E.*, xxxiv, 1903, pp. 3-67), who published evidence that the sulphides were the last constituents to solidify and not the first. This view was expressed by the author (*Presid. Address Geol. Sect. British Assoc.*, 1907, p. 499, and in 1909 at the discussion on the question at the British Association in Winnipeg; also *Geol. Mag.*, 1908, p. 40, and in "Physical Chem. Rock Formation," *Tr. Faraday Soc.*, xx, 1924, pp. 454-6). The igneous theory has been emphatically rejected as opposed to both the field and microscopic evidence by C. W. Knight (1917, *Rep. Ontario Nickel Commission*, pp. 95-285), by T. C. Phemister (*Ign. Rocks, Sudbury, Ontario Dept. of Mines*, xxxiv, 1926, pp. 1-61), and Jas. Park (*Econ. Geol.*, xx, 1925, p. 504). They point out that in addition to the sulphides having been formed after the silicates, the majority of the ore bodies are not in the gabbro, though near it, that the ores were introduced long after the intrusion of the gabbro, and that they occur in the sedimentary as well as in the igneous rocks. Phemister has shown that the micropegmatite altered both the overlying Trout Lake Conglomerate and the underlying gabbro, and that the most basic part of the gabbro is not at its lower side, as required by the igneous theory of the ore, but near the top.

The igneous formation of the ore rests on the claim that it occurs within the basic rock. Yet of the marginal ore-bodies, the lower part of the largest, the Creighton, is wholly within the granite, which was itself intrusive into the gabbro and was followed by the intrusion of quartz-diorite dykes ; and the ores were deposited later than these dykes, and are only associated with the gabbro along its shattered margin. The upper part of the Crean Hill ore-body is in granite and the lower part is along the contact between that rock and gabbro. The Victoria Mine occurs near the edge of the gabbro, but the ore is entirely in greenstone and quartzite (Fig. 36). The Levack Mine is in gneiss. The Garson Mine consists of parallel veins of ore in greenstone and schist, and partly along the contact between gabbro and greenstone. Of the off-set beds the famous deposit at Copper Cliff is a kind of pipe-lode and, according to Phemister, is an altered shattered quartz-diorite, of the same age as the last intrusions at the Creighton Mine ; it has been cemented to a breccia by the sulphides. The Worthington Mine is in similar rock that has been sheared and impregnated by ore. The Frood Mine is also a sheared brecciated band along a fault, and the ore in it occurs in all the rocks, igneous and sedimentary, traversed by the fault. In the Murray Mine the ore is the cement to blocks of gabbro.

The field evidence agrees therefore as to the formation of the ores with their microscopic structure. After the deposition of the sedimentary Animikie rocks the country was invaded by a sheet of gabbro, which was followed by an intrusion of micro-pegmatite, the junction, as pointed out by Harker, containing some mixture of the two rocks. After their solidification the country was invaded by granite and

Fig. 36.—The Victoria Mine near Sudbury.
A section through the Victoria Mine near Sudbury. The two lodes, E and W, are in quartzite and greenstone. The "norite" is to the west of the western lode. D, diabase sill (after Miller and Knight).

subsequently by dykes of quartz-diorite. Earth-movements then sheared the rocks along weak surfaces, which especially occurred beside the lower margin of the gabbro. Solutions working upward then formed the ores by partial replacement of the gabbro, and the deposition of veins and nodules of sulphides in all the rocks along the fracture planes. The ore was developed in the granite and fractured gabbro (Creighton Mine), in the greenstones (Victoria Mine), in the quartz-diorite (Copper Cliff), and in the quartzites (Frood Mine); in the Alexo Mine, 140 miles from Sudbury, similar ore was formed in serpentine. The hydrothermal formation of these nickel ores is shown not only by their microscopic structure, but by their occurrence where planes of fracture and shearing admitted the solutions after the intrusion of the quartz-diorite, the last of the four igneous rocks in the mining field. The ore is due to magmatic water—not to magmatic segregation.

NEW CALEDONIA—New Caledonia is the second nickel field as regards output. The nickel is in garnierite ($H_2(NiMg)SiO_4$), and in the green variety has replaced the iron in the serpentine, and in the brown variety the magnesium. The ore occurs to the depths of 25 to 35 feet, and is a shallow formation; it is partly in crusts which have to be broken off the serpentine masses, and sometimes as veins along the joints. The source of the nickel is unknown; it was probably not a primary constituent of the original peridotite, as so much of the serpentine is barren.

GAP MINE—The origin of nickel ores by segregation in basic igneous rock has been suggested for various fields, of which the Gap Mine at Lancaster, Pennsylvania, is of special historic interest. A band of nickel ore there occurs along part of the edge of an intrusive amphibolite. For long this mine was inaccessible, but it has been re-examined by T. C. Phemister (*Journ. Geol.*, xxxii, 1924, pp. 496-510), who has shown that the ore was not formed by differentiation in the igneous rock; for the sulphides cut across the silicates, and like the associated siderite, are later than the amphibolite; the ore was formed by replacement along many small fractures.

In Floyd County, S.W. Virginia, a dyke said to be norite, contains nickel-bearing pyrhotite and is intrusive in syenite; microscopic examination (Watson, *Tr. Amer. I.M E.*, xxxviii, 1908, p. 695) shows that the sulphides are in cracks in the dyke, and penetrate and replace the pyroxene; hence, there also, the nickel ores are later than the consolidation of the igneous rock.

South Africa—Nickel ores of no economic importance occur at Insizwa in the N.E. of Cape Colony (at 29° 20′ E., 20° 45′ S.) in an intrusive sill which W. H. Goodchild has explained as due to the separation of the sulphides from a molten norite. T. C. Phemister (*Tr. I.M.M.*, xxxiii, 1924, pp. 519-20) has shown that the rock is an olivine-gabbro with some picrite on the lower margin; and that the sulphides were not the first formed constituents in the gabbro, as they often replace biotite, occur in secondary quartz, and were deposited along fractures.

The Bushveld laccolite in the Transvaal includes disseminated and massive nickel-bearing sulphides which are regarded by P. A. Wagner as primary and magmatic; but he describes the sulphides in the ore as unquestionably later than the silicates, and as in part replacing the silicates; and the ore bodies cut across the "pseudo-stratification" of the rocks and their mineralization has been guided by older fractures (*G.S.S. Afr.*, Mem. 21, 1924, p. 147).

A small occurrence of nickel-cobalt ore in a diorite at Talnotry, near Newton-Stewart in S.W. Scotland, has been attributed to igneous segregation. The sulphides were deposited along a fault after the igneous rock had undergone great hydrothermal changes.

Mercury

Mercury—Uses and Price—Mercury or Quicksilver (Hg; at. wt., 200; sp. gr. liquid, 13·6; melting-point, — 38° F.; boiling-point, 357° F. with slow volatilization at ordinary temperatures) is the only metal which is liquid at ordinary climatic temperatures. It is used in barometers and thermometers owing to its heaviness and its regular expansion and contraction with changes of temperature. Its most extensive use is for chemical purposes, and as a drug; its other chief uses are as a pigment, a detonator—its use in percussion caps developed the fire-arm from the ancient flintlock—as amalgam in dentistry, and in mirrors. It is of great service in gold mining, as it enables minute particles of gold to be recovered by amalgamation.

Mercury is sold in iron flasks containing 75 lb. each. Its range in price from 1850 to 1918 was between £5 16s. and £26 a flask. The pre-War maximum was £21 10s. per flask in 1874. The price in 1926 ranged about £14 a flask. The average output in recent years has been from 2000 to 4000 tons mainly from the United States, Italy, which now includes the mines of Idria, Spain, and China.

ALMADEN MINES—Historically the most important mercury mines are at Almaden (Arabic, the mine) del Azogue (meaning doubtful) in central Spain. They were worked by the Carthagenians, and supplied vermilion to ancient Rome and later to the Moors; from 1525 to 1645 they were leased to the famous Bavarian bankers, the family of Fuggar. They are now worked by the Spanish Government. The mine records give the annual output since 1499.

The ore occurs in a steeply tilted Ordovician quartzite, in a series of faulted and slicken-sided rocks which range from Lower Ordovician to Devonian. An intrusive porphyry sill above the quartzite sends dykes through it. A gray crush conglomerate, the frailesca, underlies part of the ore. There are three adjacent lodes. The most important, the S. Pedro and S. Diego, is 25 feet thick and contains thick veins with 30 per cent. of cinnabar and some masses with 75 per cent. Two subparallel thinner lodes, the S. Francisca and the S. Nicolas, each yield 3 per cent. ore. The cinnabar occurs in veins along fissures and joints, and in masses due to replacement of quartzite.

The cinnabar is usually the only conspicuous sulphide; but pyrites occur in veins and grains, and forms a shell around carbonaceous nodules. The chief veinstone is quartz. The adjacent slates contain many graptolites and are richly carbonaceous, and are traversed by curved slicken-sided graphitic surfaces.

The cinnabar has been introduced in solution, probably as a double sulphate of mercury and sodium, and was deposited by the reducing action of the carbonaceous matter and by cooling near the surface. Deposition was mainly in the quartzite as its fracture produced innumerable fissures, whereas the slate was compressed into an impermeable mass. The slate contains a little cinnabar along the joints.

The main problem in connection with the Almaden ore is its age. The traditional view assigned it to the Hercynian movements mainly on the ground that the cinnabar must have been introduced before the sandstone was altered into quartzite. This change was probably during the Upper Silurian (Caledonian) movements, as the Devonian conglomerate includes pebbles of Ordovician quartzite; and the occurrence of the cinnabar along the joints, and around angular fragments of quartzite, and replacing quartz on lines crossing adjacent grains, shows that the rock was quartzite before the introduction of the mercury. Mercury ores, from the evidence of the chief fields, are formed nearer the surface than the rocks of the Almaden Mine could have been in Upper Palæozoic times. Hence if the cinnabar there were Palæozoic in age, it should have been redeposited in the Kainozoic, and its abnormal richness suggested that the present ore is a secondary concentration. Much of the San Pedro Lode yields 30 per cent. of cinnabar; the average yield at Almaden was 7 per cent.; whereas that from California was about ·3 per cent., that of Idria ·7 per cent., and of Mt. Amiata in Tuscany under 1 per cent. The Almaden lodes, however, show no evidence of the secondary origin of the bulk of the ore.

The analogy with other mercury mines is in favour of the geologically modern origin of the Almaden ore;[1] and this view is adopted by the most recent Spanish authority,[2] which assigns the ores to hydrothermal injections at the end of the Kainozoic, and after the Alpine (i.e. Oligocene and Miocene) movements. The dependence of the ores on presumably Alpine faults is shown at the eastern end of the mine, where the main lode ends against a nearly vertical fault that throws the rocks southward; Almaden agrees with other leading mercury fields in the occurrence of its ores in beds greatly disturbed by Middle Kainozoic mountain movements; but the structure is comparatively simple as the beds have been fractured and not greatly overthrust.

Idria—At Idria, near Trieste (Fig. 37), the mercury mines are in an area of geological interest owing to the early date at which thrust planes were proved there. Lipold in 1874 (*Jahrb. k. k. Geol. Reichsanst.*, xxiv, pl. 10, Fig. 1) published a section

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[1] Cf. Gregory, *J. Chem. Soc.*, cxxxi, 1922, p. 769.
[2] Minas de Almaden, *Geol. Congr. Internac.*, Madrid, 1926, pp. 67-8.

through the *Josefi Shaft*, which showed a thrust plane by which Palæozoic and Lower Triassic rocks have been pushed on to the Middle Trias. The overthrust bed is nearly half a mile wide, and must have been moved for more than that distance.

FIG. 37.—THE IDRIA MERCURY MINES.

Geological map of the district around the Idria Mercury Mines (after Kossmat); ee, Eocene-Flysch; cc, Cretaceous-Rudistenkalk; t3 t3 Upper Trias-St. Cassian Beds: Upper Trias-Wengen Beds; Dbr., Mid. Trias (Dolomite and Dolomitic Breccia) Muschalkalk; dotted, Low. Trias-Werfen Beds and Carboniferous-Gailthal Beds; . . . Faults.

Lipold's work has been in general confirmed by the later accounts of the Idria field by Kossmat (*ibid.*, xlix, 1899, pp. 259-96). The rocks belong to the Carboniferous, Trias, Cretaceous, and Eocene Systems. In the Josefi Shaft the

Lower Trias has been thrust-faulted over the Palæozoic, under which lies a dolomite breccia belonging to the Middle Trias. The ores are chiefly in the Wengen beds (Upper Trias). Fig. 38 shows that Lipold's interpretation, established by 1874, has been confirmed; the Carboniferous beds have been thrust from the N. over the Trias by the Alpine movements.

California and China—The mercury fields of California (cf. Becker, *U.S.G.S.*, *Mon.* No. 13, 1888) and of S.W. China (F. R. Tegengren, *G.S. China*, *Bull.* ii, 1920, pp. 1-36) occur in beds shattered and overthrust by the Middle Kainozoic mountain-forming movements. Minor deposits of mercury are known in many parts of the world, especially along the Alpine-Himalayan mountain system and on the western mountains of North and South America. The deposits are sometimes of very recent date: thus the Pleistocene lake deposits at Ohæawai in the Bay of Islands, New Zealand, contain veinlets of cinnabar with marcasite and traces of gold, silver, and antimony, which are being deposited by hot water in fissures (A. P. Griffiths, *Tr. N.Z.I.M.E.*, ii, 1898, p. 52).

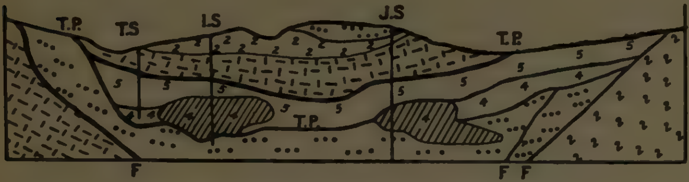

Fig. 38.—Section across the Idria Field.

Section across the Idria Field showing the thrust plane (after Bloudek). T.S., Theresia Shaft; I.S., Insaghi Shaft; J.S., Josefi Shaft; 5, St. Cassian Beds; Upper Part of Upper Trias. 4, Wengen Beds; Lower Part of Upper Trias. Main Ore Bodies, ////; . . . Middle Trias, Limestone and Dolomite. 2-2, Lower Trias-Werfen Beds. 1-1, Carboniferous-Gailthal Beds (with Land plants); FFF, Faults. T.P., Thrust Plane. According to one interpretation the rock at the base of the Theresia Shaft is a Cretaceous Limestone and the ore-body and adjacent beds have been overthrust on to the limestone.

Association of Ores with Kainozoic Mountain Movements—The mercury ores are therefore geologically young and were deposited near the surface in bands that have been intensely disturbed and fractured by mountain compression. A map of the main producing fields (Fig. 39) shows that their

FIG. 39.—THE DISTRIBUTION OF MERCURY DEPOSITS AND KAINOZOIC MOUNTAIN CHAINS.

The distribution of Mercury deposits in relation to the Kainozoic mountain chains (shown by the dark lines). The four main fields are marked by large dots and less important occurrences by small dots.

distribution is coincident with the great folding and fracturing of the Middle Kainozoic mountain system.

ANTIMONY

ANTIMONY (Sb; at. wt., 120·2; sp. gr., 6·7; melting-point, 1150° F.; volatilization-point, 2700° F.) is a minor metal of which the distribution offers an interesting contrast to that of most other ores. It is a constituent of an unusually large number of mineral species owing to its three-fold chemical valency and three oxides, the trioxide, tetroxide, and pentoxide (Sb_2O_3, Sb_2O_4, and Sb_2O_5), its readiness to form alloys, and its strong affinity for sulphur. It occurs in many sulphides combined with silver, lead, copper, mercury, and iron. It is used to harden many alloys such as Britannia metal and pewter (which contains from 5 to 24 per cent. of antimony), and "white metal" which is used for bearings. Its most important alloy is printers' metal, in which the antimony renders the type more durable and also clearer by expansion on solidification. Antimony is also used for pigments and drugs. The metal is of a silvery white colour, has a high lustre, but is too brittle for use unalloyed; it is known as "antimony regulus," and its ordinary range in price has been from £25 to £45 per ton, occasionally rising to £90; during the War owing to its use for hardening shrapnel bullets, the price rose to £130 per ton. Early in 1927 it was about £50 per ton. Owing to the large supplies available the price must be expected to fall until it exceeds the pre-war average only by the increase in cost of production.

The chief producing country is Central China, where antimony occurs mainly in the province of Hunan, S. of the Yangtze-kiang. These deposits have since 1897 enabled China to produce sometimes 90 per cent. of the world's output. The production of antimony in recent times has usually varied between 10,000 and 20,000 tons. During the War it rose to 80,000 tons. China in 1924 produced 78·3 per cent. of the world's total, the balance coming from twenty-five States. France, the second producer, yielded 4½ per cent., Algeria followed with 3·3 per cent., Bolivia 2·7 per cent., and Mexico 2·6 per cent.; the output from Australia had fallen to 1·8 per cent. The United States produces a thousandth of the supply but uses nearly half. The Chinese output may be reduced by political disturbances; but as a civil war in China usually has a less disturbing effect on business than a general election in some countries, the Chinese mines will probably maintain their output unless there be a fall in price.

THE DISTRIBUTION AND FORMATION OF ORES—Owing to the varied chemical combinations of antimony it has a wide range in distribution, from deposition as a primary constituent in deep-seated lodes, to secondary segregations and deposits near the surface. The chief commercial mineral stibnite, Sb_2S_3, containing 71·4 per cent. of antimony, is either primary or secondary. Many sulphides of antimony with lead, copper, and silver are also primary. The chief secondary minerals of commercial value are the oxides; they are sometimes associated with native antimony that has been formed by the reduction of sulphides or oxides. Stibnite is a deep-seated primary mineral in the tin-tungsten lodes of Bolivia, in gold-quartz in Bendigo in Victoria, in the Phœnix Mine at 2300 feet in Rhodesia, and in the silver-lead veins of the Harz Mountains and of British Columbia. That stibnite has also been deposited as one of the later sulphides is shown by its occurrence in cross-course veins, as in Cornwall. The main supplies of antimony come from shallow secondary deposits of stibnite, of which the distribution is similar to that of mercury.

The characteristic occurrence of stibnite is in large nodular or kidney-shaped masses often with a radial structure. They reach the size of 3000 lb. in sandstone in southern Utah; 2300 lb. in granite in Bohemia; 1200 lb. in the upper part of the Cornish copper lodes; and 500 lb. in Arkansas; large masses also occur in California, and at Whroo in Victoria; an incomplete stage of segregation is represented by the irregular bunches of ore in New South Wales.

The prolific antimony deposits in China are due to secondary concentrations near the surface. The most important mine is at Hsi-K'uang Shan in Hunan (Tegengren, *Geol. Surv. China*, *Bull.* iii, 1921, pp. 1-25). The field consists of Silurian, Devonian, and Carboniferous rocks, which have been compressed into folds and traversed by innumerable cross-fractures. The sandstones have been shattered and the fragments cemented by veins of stibnite; lenticular bodies of ore show the tendency towards nodular masses. Tegengren reports that the stibnite is a replacement of fractured rock. An essentially similar process has formed the ores at the Chiang-Ch'i-lung and Pan-Ch'i Mines, which are both in the basin of the Tze River, a southern tributary of the Yangtze-kiang in Hunan. At both localities the rocks, in addition to having been folded and fractured, have been invaded by intrusive rocks which appear to have no essential connection with the ores. The antimony at the Chiang-Ch'i-lung Mines is replaced at a depth of from 300 to 400 feet by pyrites.

The nodular masses of antimony ore are replacements by solutions moving vertically, as they are independent of the rocks in which they occur. The concentration is due to the solubility of stibnite in water at 180° F.; hence small particles are readily dissolved, and the sulphide remains in solution until near the surface, where it is deposited in a concentrated form by the replacement of various rocks. The amount of antimony in the lodes generally falls rapidly in depth, and it is replaced by various minerals such as ores of zinc in Arkansas, pyrites in some Chinese deposits, and scheelite ($CaWO_4$) in Sardinia.

ARSENIC

ARSENIC (As; at. wt., 75; sp. gr., 5·7; vaporization, 800° F.; volatilization begins at 212°) is very widely distributed as it is a constituent of 130 or about 12 per cent. of the known mineral species. Its chief ores are mispickel or arsenical pyrites ($FeAsS$), which contains 46 per cent. of arsenic; realgar (AsS), and orpiment (As_2S_3). Its main uses are to decolor glass and as a pigment, a drug, an insecticide and weed-killer, and preservative in arsenical soap. During the War it was used to harden shot, owing to the scarcity of antimony.

It is usually carried into its ores in solution, but it enters rock cavities as vapour and is deposited on the roof as small crystals of realgar. It is often associated with copper, and was produced from the upper part of the Cornish copper zone, and was found, as at Dolcoath, at a depth of 500 to 900 feet; it is deposited after tin, as it occurs in the middle crust of tin lodes and at higher levels. The main production in recent years has been in the United States, which had an output in 1924 of 13,000 tons; France was second with 10,000 tons; England produced 3200 tons from the Cornish copper mines.

BISMUTH

BISMUTH (Bi; at. wt., 208; sp. gr., 9·8; melting-point, 520° F.; it expands 2·3 per cent. of its volume on solidification) is a white hard brittle metal, which is the most strongly diamagnetic of the elements. It is chiefly found native or as the sulphide, Bi_2S_3, bismuthinite. It is used mainly for making fusible alloy, drugs, and pigments; as the demand for it is limited and closely controlled production is small. It is usually of deep-seated formation, and occurs in quartz-veins associated with tin, tungsten, copper, gold, cobalt, and uranium. As both the sulphide and carbonate are relatively insoluble bismuth ores are not readily concentrated in the surface zone. Owing to its insolubility it occurs in alluvial deposits, and is obtained in Southern China from tungsten placers. Saxony once had almost a monoply, but its yield has become insignificant; the main supplies come from Queensland, where it is obtained as a bye-product from the tin and tungsten placers, and from Bolivia, where it is obtained from tin mines. The price generally varies from between 8s. 6d. to 12s. 6d. a lb.

CHAPTER IX

ORES OF IRON

IRON—HISTORY AND QUALITIES

IRON (Fe; at. wt., 56; sp. gr., 7·5 to 7·8; melting-point, 2900° F.) is the most indispensable of all metals. It is fortunately plentiful, for it is the most abundant constituent of the earth, varying in rocks from less than 1 per cent. in ordinary granite up to 30 per cent.; the barysphere may contain 80 per cent. Native iron is rare, but is found in meteorites, and where iron oxide has been heated in the presence of carbonaceous material; it was probably first extracted from its ore by the same reaction when grains of iron oxide in sand were accidentally reduced by hot charcoal. This process was apparently first used by negroes in tropical Africa. Iron was used in Egypt in 7000-6000 B.C., according to Flinders Petrie (*J. Iron and St. Instit.*, 1912, i, pp. 182-3), but did not come into general use there until 500 B.C., when it had long been the common domestic metal in China. Its introduction to Northern and Central Europe is assigned to about 600 B.C. According to most archæologists man worked bronze earlier than iron; but metallurgists insist that some use of iron preceded that of bronze (St. J. V. Day, *Prehistoric Use of Iron*, 1877, p. 3, etc.; J. Percy, *Metallurgy. Iron and Steel*, 1864, pp. 873-4; L. Beck, *Geschichte Eisens*, I, 1884, pp. 78, 82-4).

The widespread distribution of iron and its conspicuousness as the chief colouring matter in rocks are aided by the solubility of its salts and the readiness with which iron is oxidized into rust. The latter quality, though the greatest industrial defect of iron, has rendered it available as a cheap metal owing to its concentration into high-grade ores. The mobility of iron is aided by its two oxides (ferric, Fe_2O_3 with 70 per cent. of iron, and ferrous, FeO, with 77·7 per cent.), each forming a series of compounds.

Iron is readily soluble; it is present in most spring waters, and gives many their medicinal qualities. It is present in them as bicarbonate, as sulphate, and as double salts of ammonia and humic acid, formed, in the absence of air, by organic acids. Iron is readily precipitated from these solutions; from the bicarbonates on exposure to air, and from the sulphates by organic matter, when the iron is deposited as pyrite in a dust too minute for recognition under the microscope; it causes the dark blue colour of clay, which is altered to brown or yellow on conversion of the pyrite into iron oxide. The humates may be decomposed by oxidation, iron-secreting bacteria, or decomposing organic matter.

ORE SUPPLIES—Iron near the earth's surface is subject to alternate solution and redeposition in a concentrated form as iron ore. Ninety per cent. of the available iron ores have been thus formed. According to the estimates by Eckel (*Iron Ores*, 1914, p. 41) of the world's iron ores 63 per cent. are sedimentary; 5 per cent. are normal replacements; 10·7 per cent. are contact ores or of doubtful origin; 13·3 per cent. are residual; and 7·9 per cent. are secondary concentrations. Of the sedimentary ores, 40 per cent. are Jurassic in age, 15 per cent. Carboniferous, and 16 per cent. Ordovician. Of the total iron ores of Europe (Roesler, *U.S.G.S.*, *Bull.* 706, 1921, p. 18) 35·2 per cent. occur in France owing to the enormous quantity of Lower Jurassic ore in Lorraine; the British Isles have 18·2 per cent., Sweden 12·5 per cent., Germany 11·1 per cent., and Spain 5 per cent.

The quantity of known iron ore is colossal. According to Roesler's estimate the sedimentary ores known in 1921 amounted to over 8,400,000,000 metric tons, of which France holds nearly half. The supplies already known will last for 1000 years at the output of 1913. There are still larger quantities of material which contain iron but is not regarded as ore. Whether an iron-bearing material can be used profitably depends upon its composition, the cost of fuel, and accessibility to markets. An igneous rock with 35 per cent. of iron may be of no commercial value, while material with half as much may be worth mining as an iron-bearing flux. Some iron ores are now useless owing to their high content of titanium, which can only be washed out by melting with large quantities of flux at an extravagant cost for fuel. The price of fuel is an important element in iron smelting as from 3 to 4 tons of coal are required to smelt one ton of iron. Electric smelting where there is ample water-power renders possible the working of deposits where cheap fuel is not available.

Iron ores are of unusual variety. They include materials which have been formed as igneous rock; as veins formed by ascending water and volcanic vapour; as replacement deposits formed at all depths by rising and descending solutions; as bedded ores deposited chemically or organically in sea, lakes, and swamps. The bulk of commercial iron ore has been formed by reactions which take place on or near the surface.

Classification of Iron Ores

I. Igneous Ores. Titaniferous Magnetites.
II. Contact Ores, e.g. Elba and Western America.
III. Primary Lodes, e.g. Siderites of Czecho-Slovakia.
IV. Replacement Ores—
  1. Pyritic masses. Rio Tinto, etc.
  2. Oxide Ore-Bodies due to Descending Solutions—
    (*a*) In limestones. Cumberland.
    (*b*) Bilbao.
    (*c*) Lake Superior.
    (*d*) Gellivaara and Adirondacks.
    (*e*) Mid-Sweden.
  3. Ancient surface sheets. Kiruna.
V. Bedded and Organic Ores—
  1. Aqueous precipitates. Minette of Lorraine; Clinton; British Mesozoic ores; Wabana, etc.
    Altered representatives—banded ironstones, itabirite, etc.
  2. Carbonaceous. Blackband ores.
  3. Bog Iron ores.
VI. Surface Ores—
  Efflorescent residual ores and alluvial.
  Laterites.
  Brown iron ores in residual clays.
  Black iron sands.

Igneous Ores—Titaniferous Magnetites

Veins of hæmatite, either amorphous or in brilliant crystals of specular iron, are formed around volcanic vents where iron chloride vapour is decomposed in contact with steam. Igneous ore on a larger scale may be illustrated by the hill of Taberg in Sweden, which consists of a boss of basic and ultrabasic rock. The outer zone consists of olivine-hyperite (composed of olivine, the basic felspar anorthite, and rhombic pyroxene) rich in titaniferous magnetite. The hyperite passes into the rock which Wadsworth (1882) named Cumberlandite; it contains 31 per cent. of iron and is composed of olivine and titaniferous magnetite, which are intergrown as in ordinary igneous rocks.

The iron mass at Taberg was formed as a segregation of iron oxides in basic igneous rock. It was worked, until 1870, as iron ore, and a picture of it was published in 1755 by the Royal Society (*Phil. Trans.*, xlix, p. 34, pl. ii) as a mountain of iron. Though this mass, estimated at 100 million tons, stands beside a railway 8 miles S. of Lake Wetter, it is no longer worked, as it contains too much titanium.

Enormous masses of gabbro with bands of titaniferous magnetite mixed with spinel exist in Northern Sweden and Lapland, as at Routivaara. These bands have been represented as formed by direct segregation as at Taberg; but according to Peterson they include angular fragments of gabbro, and there is no transition between ore and rock. The bands were formed after the gabbro and not as the first stage in its consolidation; they contain 68 per cent. of iron oxide, but are valueless at present owing to their 14½ per cent. of titanium oxide.

Contact Ores

Ironstones formed at igneous contacts are well developed in the Pacific coastlands of America from Alaska to Chile. They usually consist of masses of magnetite at the contact of limestone with rocks identified as diorite. The ores are actually replacements; they often contain from 45 to 65 per cent. of iron and are low in phosphorus, but may contain so much sulphur as to require roasting. The ore may include lumps of garnet and amphibole, that can be removed by hand sorting. In some places (e.g. Kennedy Lake, Vancouver Island), the igneous rock is granite, and the iron must have been brought up the contact plane and not derived from the igneous rock. (For this type of ore in Canada, cf. Lindeman and Bolton, *Iron Ores*, Canada, Dept. Mines, 1917.)

PRIMARY LODES—CZECHO-SLOVAKIA AND WESTPHALIA

Owing to the abundance of iron within the earth, and its ready solubility, it has naturally been often carried upward in solution and deposited in primary lodes. They are as a rule commercially unimportant as other iron ores are more cheaply mined.

Some lodes of specular hæmatite with sulphides of copper, lead, and zinc are associated with igneous rocks, and have been regarded as contact ores; but when neither of the rocks in contact contains much iron, the lodes must have been supplied along the contact plane. In some Tuscan localities these ores occur between igneous and sedimentary rocks; but in Elba similar ores, in large masses, lenticles and veins, replace limestones some distance from any igneous rock. The hæmatite is associated with garnet, pyroxene, epidote, and a hydrous iron-calcium silicate, ilvaite. The ores in Elba were formed after the Eocene in connection with igneous activity and earth-movements.

In Czecho-Slovakia (near 49° N., 21° E.), about 220 miles S. of Warsaw, between the towns of Wallendorf and Einsiedel, a mountain range of Devonian and Carboniferous slates and sandstones contains many fissure lodes of siderite near intrusive greenstones and granite. The lodes are of Palæozoic age and consist of siderite and quartz with tourmaline and barite. The ores are probably primary and were formed in connection with the granite intrusions. The area is in the Carpathian Mountains, and during their uplift in the Middle Kainozoic, the field was intensely disturbed, and the lodes received additional constituents including mercury.

The primary iron lodes hitherto of most value are those of the carbonate, siderite, as in the Siegerland in Westphalia, an area of Devonian slates and sandstones beside the

Sieg River, 40 miles E. of Cologne. These rocks have been intensely folded and overthrust, and broken by a network of fractures including vertical and horizontal faults (A. Denckmann, *Glückauf*, 10 April, 1926, pp. 458-67). The ore has been deposited in fissures as irregular swarms and groups of lodes. Many are small, but some are long and deep. They usually vary from 5—30 feet in width, and are sharply separated from the country, which shows but slight replacement. The fissures have been formed and re-opened at different dates and the ores are well crustified. The first filling was of siderite and quartz with some pyrite and chalcopyrite; galena and blende are rare; barite and fluorite are absent. This mineral association suggests the formation of the lodes by infiltration from the country rock, a case of lateral secretion, or by descending solutions, which are suggested by the presence of chalcocite (Cu_2S), and ores containing cobalt, nickel, and antimony. The Siegerland mines were extensively worked in the middle of the nineteenth century, until the iron works on the Rhine were supplied with cheaper ores from Lorraine; later the ore was used in Silesia.

The iron of these ores, according to one hypothesis, is derived from layers of spherosiderite that were deposited in the Devonian sea; another view considers the ores as primary lodes due to the Devonian diabase. (For the former view see A. Denckmann, *Arch. Lag.*, vi, 1912; for the latter, Bornhardt, *ibid.*, iii, 1910, and viii, 1912; for microscopic structure of the ores see Krusch, *ibid.*, viii, pp. 447-83.)

REPLACEMENT ORES

1. PYRITIC MASSES—Many valuable iron ores occur in massive ore-bodies comparatively near the surface, so that they are easily mined. One representative of this type includes the great masses of iron pyrites, but as they are worked primarily for copper or sulphur, they are considered in reference to copper ores (pp. 86-90).

2. OXIDE ORE BODIES DUE TO DESCENDING SOLUTIONS—Replacement has formed some of the most valuable iron ores.

Cumberland—The Lake District of the N.W. of England has yielded the highest grade hæmatite ores of the British Isles. They are gash-veins in the older rocks, and nodular masses and sheets in the Silurian and Carboniferous Limestones. The first group are of little economic importance. The Eskdale granite (granophyre), the Ennerdale syenite, and Skiddaw Slates are traversed by steep gash-veins of hæmatite which thin out as they are followed downwards; they have been worked in the granophyre to the depth of 300 feet. The veins thicken where two of them intersect. Some cylindrical stems made of concentric layers and known as "ring-ore" were mistaken for fossil tree stems. The ore of the gash-veins was clearly formed by replacement of the country rock by solutions descending along fissures, for the massive ore passes into iron-stained country rock, and the veins in the granophyre include unreplaced felspar.

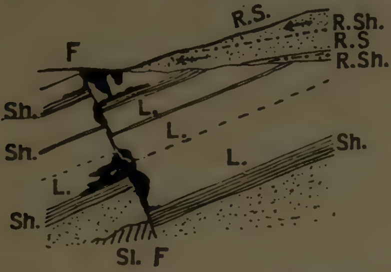

Fig. 40.—The Replacement Hæmatite Ore-Bodies of Cumberland.

R.S. and R.Sh., Permian red sandstones and shales; L., Carboniferous limestone; Sh., shales; Sl., slate; F., fault. The ore-beds are shown in solid black.

The most important of the Lake District ores are replacements in Carboniferous Limestone (Fig. 40), including large kidney-shaped masses of hæmatite (Fe_2O_3) which may contain 98 per cent. of iron oxide, with the phosphorus varying from ·02 to ·3 per cent. The ore has replaced some thin beds of limestone, bosses of which remain on the floor of the seam. In some cases limestone has been partially replaced by infiltration from overlying sandstone and the ore forms funnel-shaped masses which may spread out below into an irregular sheet. The largest ore-bodies occur along faults, which have thrown the limestones against shale; the ore is bounded on one side by the fault and passes on the other into limestone with such an irregular boundary that, according to the miner's expression, the ore and rock have "grown together." In places the ore encloses masses of limestone and beds of shale in their original position, and casts of fossil shells. These hæmatites are therefore due to replacement, but whether by ascending solutions connected with the late Carboniferous and early Permian or the Kainozoic igneous activity, or to descending solutions of post-Triassic age, has been long debated. Pebbles of hæmatite in the breccias at the local base of the Permain have been regarded as evidence that the ores are earlier than Middle Permian. The evidence is however in favour of the view that the ores were derived from the Permian and Triassic red rocks by water which percolated downward and deposited the iron in the limestones, the hæmatite in the breccias being replaced pebbles.

Bilbao—The iron mines of Bilbao in Northern Spain are famous for their high-grade hæmatite, which being low in sulphur and phosphorus was especially adapted for the Bessemer process, and was largely used in British iron-works. The mines were opened about 1865; their development was delayed by the Carlist War from 1872 to 1876, after which active mining began. The output increased rapidly and attained its maximum of nearly six million tons in 1899; there has since been a steady decline, interrupted by the War, until 1925 when the output was two million tons. The price of the ore before the War averaged about 11s. a ton. It rose during the War to 18s. 6d., but has fallen since to about 8s. About a third of the present output is spathic iron which is less profitable, as it has to be calcined from carbonate into oxide at a cost of about 3s. a ton, and calcined ore has a lower price than natural oxide. The cost of mining has moreover increased with depth, and with the narrowing of the ore.

The Bilbao iron mines occur (Fig. 41) in an anticline of Lower Cretaceous beds, which trends approximately from W.N.W to E.S.E. Its arch had been faulted parallel to the strike, and across it from N.N.W. to S.S.E. The faults have dropped blocks of limestone against the underlying sandstones, and the ore occurs in the down-faulted blocks.

The ores are mainly in a coral limestone, which is from 150-300 feet thick. Its age corresponds to the Lower Greensand. It is overlain by shales and sandstones, some of which contain pyrites and abundant nodules of clay ironstone which beside the Abandanado Mine have been altered into iron oxide. The main ore is brown hæmatite, and its banded botryoidal stalactitic structure shows that it is of secondary formation. It rests on a massive carbonate of iron which passes into the oxide and often includes lumps of limestone.

As these ores are secondary limonite, as they narrow below and rest on hummocks and pinnacles of limestone, it is natural to explain them by the replacement of limestone, and to a smaller extent of sandstone and shale, by solutions that obtained their iron from the once extensive overlying beds. The view was therefore adopted (as by F. D. Adams, *Journ. Canad. Min. Inst.*, 1901, iv, p. 202; Lindgren, *Mineral Deposits*, 1913, p. 310) that the spathic ore results from the descent of an iron solution which altered the limestone into siderite.

FIG. 41.—THE BILBAO ANTICLINE.

Section across the Bilbao anticline; the iron mine at H, between faults FF. The beds consist of Cretaceous shales containing, Cl.I., clay ironstones; Sh., shale; L, limestone; the lowest bed is sandstone.

According to an alternative view (e.g. Beyschlag, Vogt, and Krusch, *Ore Deposits*, 1916, ii, p. 833; R. W. van der Veen, *Econ. Geol.*, xvii, 1922, p. 602; R. M. de Rotaeche, *Minas de Bilbao*, 1926, p. 157), the iron is of hydrothermal origin, came up along the faults, and was deposited as siderite by the alteration of the limestone and the replacement of sandstone and shale; and this primary carbonate ore was altered to oxide by descending water. Siderite is a common primary vein mineral and often replaces sandstone, as shown by the " whinny boles " or nodules of siderite in Glasgow quarries. Where however siderite occurs as a hydrothermal product it is usually associated with copper, lead, and zinc. Thus in the hydrothermal siderite lodes of Czecho-Slovakia and the Siegerland (cf. p. 134) quartz is the chief veinstone, pyrite and chalcopyrite are frequent, while blende, galena, tetrahedrite, bornite, various nickel and cobalt minerals, and stibnite also occur. A little copper has been found at Bilbao, but the amount is small and the ordinary hydrothermal minerals are absent. The nearest igneous rocks are too remote to have taken part in the ore formation, especially as there is no ore beside them.

The Bilbao ores are therefore probably due to the percolation of descending waters along the fractures beside the down-faulted crown of the Bilbao anticline. Solutions passed through the shattered rocks, leached out their iron, and entering the limestone altered it to carbonate of iron and produced siliceous ores where the solutions entered sandstones and sandy shales. Subsequently the upper part of the ore was altered into hæmatite.

Lake Superior—The iron fields that have proved of the highest industrial importance are beside Lake Superior, and have supplied most of the ore to the iron works of Pennsylvania.[1] They still hold 2500 million tons of ore. The chief fields on the southern side of Lake Superior are those of Marquette, Menominee, and Gogebic ; on the north-western side are the Mesabi and Vermilion fields whence lower-grade iron ores, on the same geological horizon, extend eastward into Canada. The ore is mostly hæmatite associated with jaspers and chert ; some of the ore was a ferruginous carbonate with oolitic grains and greenalite, which from its analogy with glauconite, was doubtless of marine origin (Fig. 42). The Iron Formation belongs to the Keewatin Series, of which the typical rock is a basic pillow-lava. This series rests on gneisses and coarse schists with intrusive granites, and is covered unconformably by sedimentary rocks and conglomerates. The whole area of the iron fields was probably buried under the red sandstones and associated

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[1] *U.S.G.S.*, Monographs Nos. 19. 28. 36. 43. 45. 46. 52, 1892-1911.

igneous rocks of the Keweenawan. All the rocks are pre-Palæozoic, as the Keweenawan is correlated with the Scottish Torridon Sandstone. The ore is generally hæmatite, and contains usually between ·02 and ·05 per cent. of phosphorus; it occurs in very varied positions, which have one feature in common. The ore-bodies rest on an impermeable bed which may be a synclinal in slate or serpentine, or it may, as at Mesabi, fade off in irregular tongues into ferruginous or greenalite chert. The iron ore has been formed by replacement and deposited where solutions, which had dissolved iron from the overlying red sandstones of the Keweenawan or from basic igneous rocks, or from ferruginous or greenalite cherts, were stopped in their descent (Fig. 43). The bulk of the iron probably came from an oolitic chert series in which the ore was a chemical precipitate as in the Mesozoic and Clinton bedded ores.

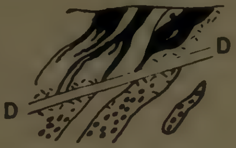
FIG. 42.—LAKE SUPERIOR IRON ORES.

The Mesabi type (after H. Garde, *Bih. Jern-Kontorets Ann.*, 1918). The ore occurs as a widespread sheet beneath an old land surface, and overlies and is partly interbedded with iron-bearing chert.

:::: Quartzite.
— · — · — Old land surface.
////// Iron ore.
▬ ▬ ▬ Iron-bearing chert (taconite).

FIG. 43.—LAKE SUPERIOR ORES.

The Lake Superior ores formed by replacement bounded below by an impermeable surface. From Cuyuna, Minnesota, (after Van Barneveld). The rocks consist of cherty iron carbonates, amphibolite, slate, diabase dyke, DD. The ore is in solid black.



The Gellivaara and Adirondacks—The famous ore-field of Gellivaara in Swedish Lapland contains massive bodies of magnetite in biotite-gneiss. The foot-wall of the chief body at Gellivaara that was being worked at my visit was sharply bounded by a fault plane with an impermeable band of clay. The hanging wall was an irregular ill-defined passage into gneiss (Fig. 44). The ore included masses of gneiss in their original positions, showing that the ore had been formed around them by replacement. The Gellivaara ores belong to the Lake Superior type, for they are due to descending water which had become charged with iron—the abundant biotite in the gneiss is the obvious source—and deposited it in masses where further descent was blocked by an impermeable layer. The ore is a valuable non-titaniferous magnetite.

In the Adirondack Mountains is another occurrence of non-titaniferous magnetite in pre-Palæozoic gneiss, schists, limestones, and plutonic rocks, which has been regarded as an igneous segregation. The ore is in lenses or pod-shaped bodies bent in harmony with the folds in the country rocks. The association of the magnetite with quartz, fluorite, apatite, and pegmatite, and its occurrence in any of the local rocks except the basic igneous rocks—in which igneous ores would be most likely—render probable a hydrothermal origin, as advocated by the author in 1924 (*Trans. Faraday Soc.*, xx, p. 454) and by H. J. Alling (*Econ. Geol.*, xx, 1925, pp. 335-63), who has shown that the magnetite is of three distinct ages, that some of it, as in the granite (see Fig. 45), is of late origin, and has replaced quartz and felspar. He concludes (*ibid.*, p. 363) that these ores are "magmatic-replacement deposits due to aqueo-igneous magnetite-rich solutions derived from a differentiating granitic magma."

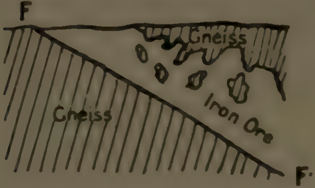


FIG. 44.—IRON ORE DEPOSITS AT GELLIVAARA.

The ore is in biotite-gneiss resting on a sheet of pug formed by a fault (F); the hanging wall is irregular; blocks of gneiss occur in the ore, *in situ*.

Middle Sweden—The iron-fields of middle Sweden, where Swedish iron and metallurgists earned their high reputation, are in metamorphosed pre-Palæozoic rocks. The rocks and ore are traversed by granite-pegmatite dykes which are also pre-Palæozoic. The mines occur to the N.E. of Lake Wener and W.N.W. of Stockholm, near the towns of Norberg, Persberg, Granjesberg, Striberg, and Dannemorra. The field consists of gneiss and schists, with halleflinta, much of which was an acid lava, a variety of gneiss known as leptite, crystalline limestones and dolomites, and "Skarn," which is a schist containing hornblende, augite, chlorite, garnet, epidote, calcite, and quartz. The ore is mainly magnetite with about 60 per cent. of iron and 1 per cent. of phosphorus, and it is practically free from titanium. The ores occur in sheets or thin lenticles, some of which are more than a 1000 yards long and 100 yards thick. The ores are often banded, and extend parallel to the country. Similar ores occur in Norway and owing to their association with igneous rocks, were claimed by Kjerulf and Dahl (1861) as eruptive in origin; but as the ore sometimes occurs as a cement between the rock fragments it is younger than the enclosing rocks, and the simple igneous theory is invalid. Origin by magmatic differentiation (Johansson) is equally impossible for ores in dolomite.

Fig. 45.—The Magnetite of the Adirondacks.

The magnetite of the Adirondacks showing the magnetite (black) replacing the felspar, P, and quartz, Q, in granite at Cook Hill (after Alling, 1925).

The usual explanation of these ores, based on their apparent conformity to the country and banded structure, is that they were sedimentary like those of the Mesozoic. H. Sjögren attributed the ores to metasomatic action by descending solutions; but as he referred the process to too late a stage this view was generally rejected.

In recent years the ores have been often regarded as contact products owing to the associated minerals, which are however equally characteristic of regional metamorphism; and the ores are not always associated with igneous rocks and some of them are isolated in limestone.

The difficulty of determining the nature of these ores is increased by the extreme alteration of the country rocks. The general relation of the ores indicates that they are replacement deposits formed under varying but comparatively superficial conditions. The simplest type is ore in limestone or dolomite, remote from igneous rock; the form of these ore-bodies recalls that of the replacement ore in the limestones of the N.W. of England. In a second and common type the ores lie in hollows with an impermeable base, like those in the pre-Palæozoic rocks of Lake Superior, due to the stoppage of descending solutions. The ore of the third type is in wide sheets conformable with the country and resting on leptite or halleflinta; this ore may have been deposited on the surface of the igneous rock as a ferruginous crust; the iron was probably leached from underlying rocks, and precipitated on the surface, and may have been supplemented by bog iron ore deposited in pools and enlarged by solutions during the metamorphism of the area and the intrusion of the granite dykes.

The non-titaniferous nature of the ores is opposed to their igneous origin. Their chemical composition and distribution are consistent with the formation of some by the processes which deposited the iron ores of Lake Superior and the N.W. of England, and of others by the processes which form iron crusts in arid lands.

3. Ancient Surface Sheets, Kiruna—The rich magnetite mines at Kirunavaara in Swedish Lapland, despite the remote position N. of the Arctic Circle (68° N., 20° E., a little S. of Lake Torneа), are of commercial importance from the high grade of the ore and the easy mining, and are of special geological interest from the widespread belief in their igneous formation. Löfstrand in 1891 suggested that the magnetite was a segregation, as at Taberg. That view became untenable when it was found that the rocks on the two sides of the ore differ in age and character. The footwall is syenite-porphyry of which the upper part shows volcanic structures. Above the ore lie quartz-porphyry lavas interbedded with tuffs and sediments. The igneous origin of the ore has been re-introduced in three forms. According to R. A. Daly (1915), the magnetite solidified in the quartz-porphyry and sank to its base. According to O. Stutzer (*Neu. Jahrb.*, xxiv, 1907) the ore is an iron oxide

dyke. According to Per Geijer (*Geol. Kiruna*, 1910, p. 269; he later adopted the dyke theory), the ore was discharged as a lava flow of magnetite.

One essential fact is the occurrence along the base of the quartz-porphyry of fragments of all the varieties of the underlying ore. The ore was therefore in existence before the first quartz-porphyry lava flow. Prof. Daly's theory is attended by the difficulty that the quartz-porphyry contains only from 2·9 to 8 per cent. of iron oxide, and the lowest flow, which could alone have supplied the ore, could not have provided the quantity in the lode; and that porphyry still contains a normal amount of iron.

Fig. 46.—The Ore-sheet of Kirunavaara, Swedish Lapland.

Sy.P., syenite-porphyry; solid black, the ore, sharply bounded above, with occasional secondary spurs passing upward. Q.P., the quartz-porphyry, of which the lower flow contains at the base angular fragments of the ore; C.S.T., conglomerate, sandstone, and tuff; S., quartzite.

The iron ore pebbles in the quartz-porphyry favour the formation of the ore by some aqueous agency. The sheet of ore (Fig. 46), though sharply separated from the quartz-porphyry, passes down gradually into the underlying syenite-porphyry; the iron appears to have been dissolved from the underlying syenite and deposited on its surface as a sheet of phosphatic bog iron in a swamp, as suggested by W. H. Herdsman (*Journ. Ir. and St. Inst.*, lxxxiii, 1911, p. 480), or as a deposit from hot rising water, as suggested by Bäckström (*Geol. För. Stockholm Förh.*, xxvi, 1904, pp. 180-5), or as a sheet of surface ironstone formed by evaporating water.[1] Bäckström described the process as pneumatolytic

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[1] De Launay, *Ann. Mines* (10), IV, 1903, p. 98, regarded the ore as sedimentary. A new paper by Vogt (*G. For. Forh.*, 1927, pp. 153-95) urges the intrusive nature of the ore, regarding the ore fragments as segregations.

and regarded the hot water as derived from the syenite; but the pneumatolytic minerals are very exceptional, and the water probably acted at a lower temperature. The explanation which on a visit to the field in 1907 appeared to the author best to explain the facts is that the ore was deposited as a surface sheet of hæmatite by water that percolated through the syenite-porphyry, and that the sheet of ore had been thickened on the under side by secondary replacement, probably when the apatite veins and occasional tongues of ore were deposited in the quartz-porphyry. This explanation is consistent with the gradual passage of the ore into the syenite-porphyry, with the sharp separation from the overlying quartz-porphyry, with the phosphoric and practically non-titaniferous nature of the ore, and with the occurrence of the pebbles of the lode in the base of the overlying quartz-porphyry.

Superficial sheets of ore, especially those of organic origin (cf. p. 145), are characterized by a high proportion of phosphorus just as the igneous ores are characterized by their richness in titanium. The bulk of the Kiruna ores is estimated to contain from 1½ to 2 per cent. of phosphorus, and this argument for its organic origin has been emphasized by W. H. Herdsman. Deposits of such antiquity in an area which has undergone such changes and earth-movements naturally show marked differences from analogous modern deposits. The apatite has been dissolved and redeposited in streaks in the ore and as veins and replacements in the quartz-porphyry. At the same time some iron has been dissolved and redeposited in places as tongues protruding into the quartz-porphyry. These have been described by Per Geijer as dykes, but that explanation is inconsistent with the pebbles, of which the evidence seems the more weighty.

THE BEDDED IRONSTONES—AQUEOUS PRECIPITATES—About 80 per cent. of the known supplies of iron ore are interbedded in sedimentary rocks. They include the British Jurassic ores which have played a leading part in the discussion on these ores owing to their accessibility, early economic importance and variety; the Liassic minette of Lorraine, which is the largest reserve of iron ore in Europe; the Clinton oolitic hæmatites of Ordovician age in Alabama, which occur in a basin about 50 miles by 10 miles in area and are estimated to amount to 5000 million tons of ore with from 50 to 55 per cent. of iron, and from ·2 to ·7 per cent. of phosphorus; and the Wabana ores of Bell Island, Newfoundland, which are also Ordovician, and their five beds, varying from 5 to 20 feet in thickness, along a three-mile outcrop, contain, according to A. O. Hayes (*G.S. Canada, Mem.* 78, 1915), between 2000 and 3000 million tons of ore with about 53 per cent. of iron and ·85 per cent. of phosphorus and 7000 million tons of lower grade ore.

These bedded ores have proved one of the puzzles of sedimentary petrology. The banded ironstones, which consist of thin layers of quartz and hæmatite or magnetite, in the pre-Palæozoic rocks of India, Western Australia, and Africa, and the Itabirites of Brazil, are probably altered representatives of this type.

The bedded ores are generally associated with iron silicates including glauconite, and also chamosite and thuringite which are chloritic hydrosilicates of alumina and iron oxide (FeO). Some of the oolitic grains contain a skeleton of silica that indicates their formation from silicates, and conversion into ore during the formation of the deposit. These bedded ironstones have been generally formed under shallow water marine conditions. The Clinton and Wabana ores contain marine shells and Bryozoa replaced by Hæmatite, and the mud-cracks and ripple-marks show that the deposits were occasionally above water; the deposition may have been under lagoon conditions. Three chief explanations have been offered of these ores. According to the first, the metasomatic theory (Sorby, Hudleston, and later Hatch and Rastall, *Petrol. Sed. Rocks*, 1913, pp. 210-12), they are limestones altered to carbonate of iron, and perhaps later to oxide. The second explanation of some of the ore was by saturation and partial replacement of sandstone by carbonate of iron (Judd). These conclusions rested mainly on the oolitic grains and marine shells which were formed as carbonate of lime. These explanations are inadequate as many of the oolitic grains had been altered into hæmatite before they had reached their present position, and their matrix shows no sign of alteration by infiltration.

The third theory is that the ore was formed by precipitation on to the sea floor of iron carbonate (which occurs in the beds as rhombohedra of siderite), and of iron oxide and ferro-silicates. The precipitated iron would have been mixed with oolitic grains and shell fragments and have converted them into iron carbonate, which has been in some places altered into hæmatite, and in others further reduced to magnetite. The origin of the iron as a direct precipitate has been adopted by many authors, including A. F. Hallimond for the British Jurassic ironstones (*G.S. Gt. Brit.*, *Spec. Rep. Min. Res.*, 29, 1925, pp. 11-14) and by G. Linck (*N. Jahrb. Min.*, Beil. Bd., xvi, 1903, p. 497), and Eckel (*Iron Ores*, 1914, pp. 58-69). It was adopted by Cayeux (*Etude Petrog. Roches Sed.*, Paris, 1916) for the Minette of Lorraine, but in his later monograph (*Les Minerais de Fer Oolithique de France*, Fasc. II, Paris, 1922) he attributes the precipitation to bacteria, and this view has been accepted by Dr. Rastall (*Geol. Mag.*, 1925, p. 91). There is no direct evidence for the bacteria, and the main argument for their action is that the abundant fossils in the ore indicate that the sea-water cannot have contained sufficient iron for precipitation except by organic agency. The inorganic precipitation of the iron salt need have been no more rapid nor required a greater concentration of iron in the sea-water than in the formation of glauconite, which takes place on sea floors rich in organisms. The ore was formed apparently on shoals or in shallow basins whence most of the clay and silt were swept away ; accumulations of oolite grains and shell fragments were buried in the wave-concentrated iron precipitate. The calcareous constituents were altered into hæmatite by the material in which they were imbedded and not by iron solutions that infiltered from outside.

Blackband Ores—Some sedimentary iron ores are of indirect organic origin, such as the blackband ironstones found in the coal-fields of the S.W. of Scotland, which contained so much carbonaceous matter that they were smelted without additional fuel. They usually consist of a breccia of ironstone fragments in clay ; they were formed on the floor of a swamp or lagoon by the alternate deposition of carbonate of iron and coaly carbonaceous mud. As the beds shrank owing to the loss of water and compression, the ironstone crusts were broken and the fragments surrounded by the mud.

Bog Iron Ores—The famous microscopist, Ehrenberg, described as *Gaillionella ferruginea*, a fresh-water alga with stems charged with hydrous iron oxide, which has been regarded as a normal secretion of the living organism like the carbonate of lime in shells and coral. A. Gages has described a mould, *Penicillium*, that grew in the tanks of the College of Science, Dublin, and extracted so much iron that if burnt it left a skeleton of hydrous iron oxide. According to some authorities the deposition of the iron oxide in these plants is a post-mortem process due to the reduction of iron salts by the decomposing tissues. According to D. Ellis (*Iron Bacteria*, 1919, pp. 191-2, p. xvii, etc.) the living iron bacteria secrete iron directly and thus help the formation of bog iron ore; but according to H. Mölisch (*Pflanze in Beziehungen zum Eisen*, 1892, p. 80) their contribution is insignificant, and usually nothing.

Bog iron ore though of good quality occurs in comparatively small quantities. The most important deposits were those in the Swedish lakes which are renewed and re-dredged at intervals. Larger masses occur in many parts of the world, such as the Hill of the Pines, or Mesa de los Pinos, at Rio Tinto; it contains fossil leaves and was deposited in a swamp from iron derived from the adjacent masses of pyrites.

Surface Ores—Efflorescent, Residual, and Alluvial Ores—Superficial sheets of iron ore are widespread. They occur as residual deposits left by the solution of limestone as in Franconia; as a sheet of sphærosiderite or crust of hæmatite which breaks up into ironstone or "crowfoot" gravel, over weathered basalt; as crusts or concretions of ironstone formed as efflorescent deposits over sandstones or sands; as laterites due to evaporation during the dry season of water which has soaked into iron-bearing aluminous beds; as the sheets of nodular hæmatites in some of the rich ores in Bengal. These ores are high in phosphorus, usually ranging from ·2 to 2 per cent., and are low in titanium.

Alluvial iron ores are concentrates of iron oxides on river beds and sea beaches, such as the black iron sands due to the disintegration of igneous rocks containing magnetite. These black sands are collected in alluvial mining, but as the magnetite is titaniferous they have hitherto been of no commercial value, though they may be useful now that titanium oxide is used as a paint.

CHAPTER X

ORES OF MANGANESE AND CHROMIUM

MANGANESE

THE ores of manganese (Mn; at. wt., 55; sp. gr., 7·7; melting-point, 2275° F.) are constantly associated with those of iron. Its main service is as an alloy with iron, which it hardens and strengthens; it is used as a flux, a pigment, in drugs, and in chemicals. Manganese is widely distributed in rock-forming minerals, as in the pyroxene rhodonite ($MnSiO_3$; Mn 41·8 per cent.), hortonolite, a variety of olivine, and spessartite, manganese-garnet. Like iron it readily oxidizes, and is deposited in sedimentary beds, as replacements, and as earthy mixtures of hydrous oxides, such as wad and psilomelane. The black oxide, pyrolusite, (MnO_2; Mn 63 per cent.) occurs as a black stain and in dendrites, the plant-like growths on joint planes. The manganese carbonate, rhodochrosite ($MnCO_3$; Mn 47·8 per cent.) is a common veinstone. Manganese is sparse in most igneous rocks, but abundant in those of certain areas; thus the Kodurite Series of India ranges from acid to ultra-basic, but all its rocks have above the average proportion of manganese (L. L. Fermor, *G.S. India*, ***Mem.*** xxxvii, p. 250). The ready concentration of manganese helps its deposition in lodes along faults or fissures, as in Central Germany and Japan, and in nodular replacement masses, as in the Kodurite Series of Vizagapatam in India. Manganese ores, like those of iron, occur under very varied conditions; but those of most economic value are secondary concentrations derived originally from igneous rocks. The bedded ores have been mined from many geological horizons, e.g. the Ordovician of North Wales, the Devonian of North Devon, and near Coblenz and Giessen, in Germany, the Oligocene at Nicopol in Southern Russia, and the Lower

Eocene sandstones of the Southern Caucasus. Manganese ores, probably also of sedimentary origin, occur in pre-Cambrian metamorphic rocks, such as spessartite beds in the Gondite Series in India, and the extensive deposit at Wigg, in Minas Geraes in Brazil.

Manganese deposits are still being formed in the sea; nodules of pyrolusite due to the decomposition of volcanic fragments litter the ocean floor and grains and nodules are formed in shallow seas, as in Loch Fyne, by precipitation from river water.

The residual ores are economically the most important. They occur where manganese disseminated through a rock has been concentrated by removal of the rest. Thus the Silurian Batesville Limestone of Arkansas contains manganese which has been left as nodules where the rock has been dissolved (R. A. F. Penrose, *Ann. Rep. G.S.*, *Arkansas*, for 1890, i, 1891, p. 177). The botryoidal manganese ore of the Lafayette district of Brazil is regarded by Miller and Singewald (*Min. Dep. S. Amer.*, 1919, pp. 182-3) as residual from a siliceous pre-Cambrian limestone. The manganese ores of Bahia are attributed by the same authors (*ibid.*, p. 189) to the superficial decomposition of rocks containing manganese. This process has also formed the manganese ores with the laterites of tropical countries, such as India, East Africa, and the Gold Coast. The high-grade Gold Coast ore is residual and due to the weathering of phyllites, schists, and a quartzite containing spessartite (Kitson, *Gold Coast G.S.*, *Bull.* i, 1925, pp. 12-16). Lateritic ore often contains so much iron that it is sold as manganiferous iron ore. Iron and manganese ores present a gradual passage from iron ore containing less than 5 per cent. of manganese, through manganiferous iron ores containing between 5 and 30 per cent. of manganese and over 30 per cent. of iron, and ferruginous manganese ores containing from 25 to 50 per cent. of manganese and from 10 to 30 per cent. of iron, to manganese ore which contains over 40 per cent. of manganese and less that 10 per cent of iron.

The price of manganese ore is fixed by the unit or percentage of manganese. Usually the ore must contain 50 per cent. of manganese, but 45 per cent. ore is used; before the War the price varied from 9d. to 1s. for each unit in the percentage of manganese; the price in 1920 rose to 3s. 10d. per unit, and since then has varied between 1s. and 2s. per unit. There is a deduction if the silica is more than 8 or 10 per cent., and the phosphorus more than ·1 per cent.; 10 per cent. of alumina and potash is usually the maximum accepted.

The leading manganese-producing countries now are India, Brazil, Southern Russia and Georgia,[1] and the Gold Coast. Extensive deposits are known elsewhere as in East Africa, and many low-grade ores were mined during the War in the southern part of the United States. [For literature see the monograph by Fermor, *Mem. G.S. India*, xxxvii, 1909; R. A. F. Penrose, *Ann. Rep. G.S. Arkansas*, for 1890, i, 1891; and L. Demaret, *Les Principaux gisements des Minerais du Manganèse*, *Ann. Mines Belgium*, x, 1905, pp. 809-901.]

CHROMIUM

Chromium (Cr; at. wt., 52·5; sp. gr., 6·5; melting-point, above 4500° F.) is mainly used as an alloy with steel, which 2 per cent. of chromium renders very hard and so tough that it may be bent cold. The addition of 13 to 14 per cent. of chromium makes rustless steel. Chromium compounds are used in dyeing, tanning, and bleaching. The chief mineral is chromite (FeO, Cr_2O_3), which is a primary constituent of ultra-basic igneous rocks. The ore occurs as veins, lenticular nodules, and nodular masses in pre-Palæozoic igneous rocks that have been altered into serpentine or talc-schists, and occasionally as veins in unaltered basic rocks. The most important supply at present comes from Selukwe in Southern Rhodesia, where it occurs (A. E. V. Zealley, *Tr. G. Soc. S. Africa*, xvii, 1916, pp. 60-74) in lenses in talc-schists, and as granular patches in serpentine. Formerly the largest production was in New Caledonia, from veins or pockets in serpentine, and residual surface accumulations. The Canadian chromite mines may be illustrated by that at Lake Caribou near Thetford, Quebec. The ore is in serpentine, in a 30-foot band which has been intensely altered and charged

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[1] A recent account of the commercial aspect of the Georgian deposits is given by D. Zeretelli, *Manganese Ore with Special Reference to Georgian Ore*, London, 1925, 136 pp.

with so many veins of chromite that it has a stratified aspect. The adjacent serpentine is intensely broken and slickensided. The ore band yields about 7 per cent. of chromic oxide, but nodular expansions of the veins contain 50 per cent. Some veins of an acid rock with vesuvianite project from the ore into the serpentine. The ore was formed after the consolidation of the peridotite of which the serpentine is the altered representative, and the chromite veins were deposited in a band crushed by earth-movements[1] (Cirkel, *Chrome Iron Ore*, Quebec; *Canada Dep. Mines*, 1909).

Chromite occurs in Beluchistan, Mysore, etc., also in serpentine in veins which are presumably later than the rock. In California, at Little Castle Creek, the chrome ore is in a serpentine formed from pyroxenite; the lower part of the rock is too poor to be mined, and the ore is just below the outcrop, as if concentrated by secondary enrichment.

As chromite is a primary constituent of basic rocks, its ores have been often regarded as igneous segregations. This origin appears probable for some cases. Thus in the gneiss of Maryland an intrusive peridotite, which contains no chromite but ·5 per cent. of chromic oxide, is surrounded by an irregular sheath of chromite which is attributed to its concentration in the quickly cooled margin of the magma (Pratt and Lewis, *N. Carolina G.S.*, i, 1905, pp. 370, 372). Nevertheless the ores of most economic importance, whatever may have been the original source of their chromite, are secondary; they are found in veins and nodules that were formed after the country had been altered to serpentine, and even after that rock had been fractured. The slicken-siding of the lenses and masses of ore shows their association with earth-movements, which by crushing the rock rendered possible the concentration of its scattered grains of chromite.

The price of chromium ore is based on the percentage of chromic oxide (Cr_2O_3). Ore shipped from Southern Rhodesia containing 52 to 54 per cent. has been sold at the port of shipment since 1914 at from 43s. to 89s. per ton; poorer ore is used as a refractory material for lining furnaces for smelting iron.

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[1] Dresser considers that the dislocations were later than the segregation of the chromite though recognizing the vesuvianite as pneumatolytic (*G.S. Canada*, Mem. 22, 1913, pp. 74-95).

CHAPTER XI

ORES OF ALUMINIUM INCLUDING BAUXITE

Aluminium—Uses and Separation—Aluminium (Al; at. wt., 27·1; sp. gr., 2·6; melting-point, 1210° F.; tensile strength about 17 tons per square inch; electrical conductivity about 61½ per cent. that of copper) is the commonest metal in the crust of the earth, and in the whole earth is less abundant only than iron. Its many useful properties will doubtless render it second only to iron in service to man. Owing to its strong affinity for oxygen it always occurs in nature as compounds, and its separation as a metal has been achieved with difficulty. It has a beautiful silvery white colour and does not tarnish. It is light and can be drawn out into thin sheets and wire. It resists corrosion by organic products, so that it can be safely used for the cooking and preservation of food. Its electric conductivity is so high in proportion to its weight that it may provide the cheapest electric cables. Its great affinity for oxygen renders it a powerful reducing agent, and owing to the high heat (5500° F.) generated by the oxidation of fine aluminium powder it is used for welding, as a violent explosive, and as an incendiary material. It unites with other metals in many alloys invaluable from their combined lightness and strength.

Aluminium was isolated in small globules in 1845, and its production was begun in 1854 by St. Claire de Ville; but it was first prepared on a commercial scale in 1885, and its production was increased by the electrolytic processes of Héroult (1886) and Hall (1892); it was obtained by the fusion of cryolite, the double fluoride of sodium and aluminium mined from a vein in gneiss in Greenland. The employment of aluminium on a great scale only became possible after the Bayer process enabled it to be extracted electrically from bauxite, of which there are large supplies in the tropics and warm temperate zones.

The production of aluminium has increased rapidly in recent years; the total output in 1913 was 70,000 tons, which the stimulus of the War raised to 178,000 tons in 1918, and after a fall to 67,000 tons in 1921, increased to 190,000 tons in 1925. The modern production is mainly from the mixed mineral bauxite, which was described by Berthier in 1821 from Les Baux near Arles in the S. of France; it contains 52 per cent. of alumina. An allied material from Southern India had been named laterite by Buchanan in 1807; it is an oxide of alumina associated with ferric oxide, titanium oxide, and water. Laterite is a superficial decomposition product of various rocks, and especially basalt, in warm countries with a long dry season.

Bauxite—Bauxite has been often regarded as a mineral species with the composition Al_2O_3, $2H_2O$, and therefore intermediate between diaspore, Al_2O_3, H_2O, and gibbsite, Al_2O_3, $3H_2O$, and also allied to wocheinite, $2Al_2O_3$, $3H_2O$. Some bauxite is a mixture of equal parts of gibbsite and diaspore, and some of that in India, according to C. S. Fox (*Mem. G.S. India*, xlix, 1923, p. 21) consists of gibbsite mixed with amorphous alumina and iron oxide. Bauxite and laterite pass into one another, the laterite having more iron and bauxite more alumina. Both are formed by the decomposition of silicate of alumina and removal of silica. Silicate of alumina is usually stable, but is decomposed in nature by three processes. Where rain-water soaks into the ground and acts upon it slowly in the presence of carbon dioxide and organic matter or—as suggested by Sir Thomas Holland (*Geol. Mag.*, 1903, p. 63) of primitive organisms such as bacteria—the silicate is decomposed; the water carries silica into the rivers in solution (e.g. Sir J. B. Harrison, *Rep. Geol. Brit. Guiana*, 1898, p. 19), or deposits it as veins of quartz, leaving free alumina which is widespread in tropical soils. The alumina is often deposited in rounded concentric bodies or pisolites. This process is especially effective where hot dry seasons alternate with periods of heavy rain, where the slope is gentle, so that the rain soaks into the ground, and at levels, as below 5000 feet in India, where the average temperature is high throughout the year.

Bauxite is therefore chiefly developed on tropical plains and low plateaus, and it is often associated with laterite; for the ground-water dissolves iron and deposits it at the surface when it evaporates during the dry season. This process forms a bed of laterite overlying bauxite, which passes through the stage of lithomarge into the bedrock.

A second mode of bauxite formation is, as at les Baux (Fig. 47), by the action on clay of sulphuric acid set free from decomposed pyrites; the acid acts on the silicate of alumina and forms alum (a double sulphate of aluminium and potassium) and aluminium sulphate; they are carried up into the limestone, and deposited as veins and pockets of bauxite. A third mode is by the action of alkaline solutions which, rising up fault planes, act on the wall rocks, remove the silica, and leave a vein of alumina.

FIG. 47.—DIAGRAM OF THE VARIOUS PROCESSES OF BAUXITE FORMATION.

Vein due to ascending solution. Pockets of bauxite in limestone due to sulphuric acid rising from pyritic shale. Surface action forming sheets of bauxite beneath laterite and overlying lithomarge. In the left part of the section is a bed of redeposited sedimentary bauxite.

Secondary or detrital bauxite is formed by the washing of primary bauxite into lakes, where it is deposited in beds associated with ordinary clay, and by residual nodules of bauxite being left on the removal by solution of a bed of limestone.

In the British Isles the best-known bauxites occur in sedimentary beds between two series of basalts in north-eastern Ireland; the bauxite is of low grade, mostly containing under 52 per cent. of alumina, and both silica and titanium are often high. In Scotland, near Saltcoats, pisolitic bauxitic clay containing from 35 to 52 per cent. of alumina has been formed by the alteration of Carboniferous volcanic ash.

Bauxite is named from les Baux, near the mouth of the Rhone, where it occurs as a bed 30 feet thick and as pockets in Lower Cretaceous; it is high in silica and alumina, and is used for the manufacture of alum, while the detrital bauxite of the adjacent district of the Var, being low in silica, is extensively used for the extraction of aluminium. Bauxite is abundant in Southern Europe from Spain, where it has been formed by hydrothermal action on the Lower Eocene rocks of Catalonia, to Rumania, where it occurs in beds and masses in the Upper Jurassic limestones which have been intruded by granite and rhyolite and faulted and tilted by mountain folding.

The United States produces the largest annual output of bauxite, mainly in the southern states. The transition may be seen in Arkansas from pisolitic bauxite to material which retains the structure of nepheline-syenite. Some bauxite has been redeposited in Kainozoic times as detrital beds, some of which are valuable by being very low in titanium. In Georgia and Alabama, bauxite occurs as masses in residual clay overlying the Lower Palæozoic Knox Dolomite, which has been turned into chert by silica being carried into it during the formation of the bauxite. In Georgia the Cretaceous and Kainozoic beds contain bauxite which, according to Veitch, were clays that have been altered by descending alkaline waters. Some Georgian bauxite contains seams of pyrites deposited by solutions after the conversion of the original rock into bauxite.

British Guiana is one of the chief producing countries of high quality bauxite, which is there due to the decomposition of dolerite, granite, and horneblende-schists. The high-grade bauxite of Mt. Ejuaneme on the Gold Coast (with 64 per cent. of aluminium, ·25 per cent. of ferric oxide, ·5 to 3 per cent. of silica, and from 1·3 to 3·6 per cent. of titanium oxide) has been formed from the decomposition of shale. Widespread deposits in other parts of Africa, India, and Western Australia are also due to the decay of old rocks by meteoric waters.

The chief uses of bauxite are for the production of alumina and alum, for firebricks and furnace linings, for the filtration of petroleum, as after heating to between 750° and 1100° F., it absorbs colouring matter and sulphur, and for quick-setting cement, *ciment fondu.* This cement is very resistant to chemical attack, sets in as many hours as Portland Cement takes days, consists of calcium silicate mixed with calcium aluminate, and is made by the electric fusion of bauxite and limestone. Bauxite is usually mined by those who use it, so that there is no common market price; the value depends on the percentage of free alumina, with deductions for high percentages of silica, iron, and titanium oxide. The highest grade bauxite ranges from 60 to 65 per cent. of alumina, with 1 per cent. of iron oxide, and 2 to 5 per cent. of silica; most of it is used for the manufacture of aluminium for which the usual minimum is 52 per cent. of alumina, not over 3 or 4 per cent. of silica, 2 or 4 per cent. of titanium oxide, or over 6·5 per cent. of iron oxide. The second largest quantity is used for alum, for which the essentials are little titanium and iron, and no chromite. The qualities preferred are as follows:—

For Manufacture of	Al_2O_3.	SiO_2.	Fe_2O_3.	TiO_2.
Aluminium	+ 52 per cent.	− 4½ per cent.	− 6½ per cent.	− 2 per cent. or 4 per cent. in highest grades.
Alum . .	+ 52 per cent.	− 10 per cent.	low	low, no Cr_2O_3.
Refractories	+ 40 per cent.	− 15 per cent.	low	—
Cement . .	+ 45 per cent.	+ 10-15 per cent.	10 per cent.	—

PART III

EARTHY MINERALS

CHAPTER XII

THE MICAS, ASBESTOS, AND GEMS

THE non-metallic minerals include many species of value from special physical and optical properties.

THE MICAS

DISTRIBUTION AND USES—The micas are anomalous in distribution; they are ubiquitous in minute flakes, being essential constituents of many abundant rocks, such as granite, gneiss, mica-schist, minette, and kersantite, being common in micaceous sandstones, forming the bulk of some clays, and giving the blue colour to the Swiss lakes. Nevertheless mica of industrial service is exceptionally local; it is found only in deep-seated pre-Palæozoic rocks; 70 per cent. of the world's supplies comes from one district in India, and most of the rest is from two or three localities.

The chief uses of mica are for windows and lampshades, where heat or vibration are too great for glass, and as an insulator in electrical machinery. The most useful micas are the white mica, muscovite, and a brown species, phlogopite. Muscovite is usually found with pegmatite, as in Bihar and Nellore in India, in the Transvaal, Tanganyika Territory, Kenya Colony, Brazil, Quebec, the Eastern United States, and Russia.

PNEUMATOLYTIC ORIGIN—The mica of Bihar is found with sheets, " blows " or lenticles, and irregular masses of pegmatite in schist and gneissose granite. Pegmatite is sometimes injected as a molten intrusion; but some occurrences are isolated in schist or gneiss, and must have been formed by its recrystallization. As the mica is associated with tourmaline, fluorite, topaz and china-clay, it must have been formed pneumatolytically by super-heated steam containing boric and fluoric acids. The original rock has been replaced by huge crystals of quartz, felspar (usually microcline), and " books " of mica. The quartz may form the core of a mass or the middle of a sheet of pegmatite (Fig. 48). The mica books usually occur at the contact of the pegmatite with this quartz or with the country, especially where the country rock is strongly micaceous.

Phlogopite, a brown magnesian mica, is of especial value for electrical purposes because it is softer than muscovite and rubs away at the same rate as copper. Bearings with phlogopite insulators wear evenly. The chief field is in Ottawa, Canada, where the gneiss and crystalline limestones are intersected by veins or masses of pyroxenite. According to some authorities (e.g. A. Osann, *Ann. Rep. G.S. Canada*, xii, 1902, p. 21) the pyroxenite is intrusive; according to F. D. Adams and Barlow (*G.S. Canada*, Mem. 6, 1910, pp. 88-90) it is altered limestone. In some cases, such as the Loughboro' Mine (Fig. 49 after Schmid, Mica, *Canada Dept. Mines*, No. 118, 1912, p. 147), the pyroxenite would appear intrusive into the gneiss; both rocks were covered unconformably by limestone; subsequently superheated acid water containing magnesia rose through the pyroxenite and

Fig. 48.—The Formation of Mica in Gneiss, Kenya Colony.

(Gn.), A pegmatite vein (P) with isolated pegmatite bodies (P) in the gneiss. The core of the pegmatite consists of quartz, Q. Muscovite " books " especially abundant near the quartz.

formed a seam of coarse calcite containing books of phlogopite. In other cases the mica has been developed in dykes on the margin of pyroxenite. The age of the mica is pre-Cambrian as some lodes are cut off unconformably by the Cambrian rocks.

Mining Economics—Few mica fields can compete with India owing to the cheapness and efficiency of Indian labour. As the value of mica varies with the quality and size of the cut pieces, the economics of mica mining do not depend on the weight of output. The mica is usually won by small pits sunk along the margin of the pegmatite blows or veins. The mica is of little value where it is most abundant, for the books are interwoven and do not yield large leaves. The rough mica crystals are split into thin leaves, which are cut into the largest sizes possible after imperfections are removed and the edges trimmed. The pieces are graded into sizes. Those of No. 7, about 1 inch square, are used as washers in

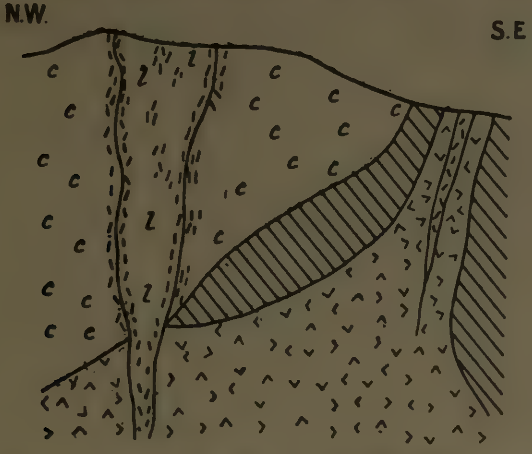

Fig. 49.—Phlogopite Lode at Loughborough, Canada.

Pyroxenite (*v*) intrusive into gneiss (inclined lines) and overlain by an altered limestone (*c*). A lode (*l*) of coarsely crystalline calcite rises from the pyroxenite and includes and is bounded by mica books (short strokes). A smaller lode with mica occurs in the pyroxenite. (After Schmid.)

electrical apparatus, and worth sometimes 7d. per lb.; No. 1 contains pieces of 24 to 36 square inches and are worth, according to clearness, from 10s. to 30s. per lb.; extra special sizes may sell for 37s. per lb. The economics of mica mining may be illustrated by the results at Kodarma in Bihar. Each miner obtained an average of 32 lb. of rough mica per day; this yielded 4 lb. of cut mica. If this had all been No. 7 mica at 7d. per lb., the yield would only have been 2s. 4d. per man, but its average price before the War was 9s. per lb., and as wages were 6d. per day, the yield was profitable.

ASBESTOS

Asbestos (from a Greek word meaning inextinguishable) is a fibrous mineral which is non-inflammable, and a bad conductor of heat, and is produced by the decomposition of several magnesian silicates. Flexible fibres are woven into fireproof cloth; others are used for making heat-proof tiles and packing, filters, and cement; the largest use at present is in motor car brakes and clutches.

The most important variety is chrysotile asbestos, a fibrous serpentine worked chiefly in Canada, Rhodesia, the Ural Mountains, and Cyprus. The main asbestos field is at Thetford and Black Lake in Quebec. The asbestos occurs in veins in a thick sill of Devonian peridotite, diabase, and porphyry, which contains veins and masses of pegmatite, granite, and aplite. The best asbestos is said to occur abutting against the aplite, and asbestos tufts occur in its quartz. The serpentine is due to the alteration of peridotite, and contains masses and lenticular streaks of it. The serpentine is traversed, often along shearing planes, by veins of asbestos up to 3—6 inches thick. The fibres are at right-angles to the vein, and have formed by recrystallization of the serpentine along both sides of a fissure. A variety, locally called fibrolite, at the Vimy Ridge Quarry has longer but more brittle fibres. The asbestos has been worked in long open cuts, now 350 feet deep, and has been proved by boring down to 800 feet. The fibre is separated from the crushed rock by shaking tables and air suction, and amounts on an average for the district to 4 per cent. of the rock. Tremolite or Italian asbestos is worked in Piedmont, and has fibres 2—3 feet long; it is more resistant to acid, but is weaker than chrysotile asbestos. Anthophyllite asbestos (from a rhombic amphibole) is a brittle variety quarried in Georgia (U.S.A.) for use in building tiles. A. M. Bateman (*Econ. Geol.*, xviii, 1923, pp. 663-80) has described an Arizona asbestos due to replacement of thin bands of serpentine which had been formed along earthy layers in a limestone by magmatic water from an adjacent diabase. This serpentine was not an altered ultra-basic rock.

The value of asbestos varies greatly; in 1925 the average of all grades was about £7 per ton, while the highest quality was worth about £100 per ton.

MONAZITE

Monazite ($Ce(LaDi)PO_4$; sp. gr., 5·2; hardness, $5\frac{1}{2}$) is a phosphate of the rare earths cerium, lanthanum, and didymium, and yields the thorium oxide used for gas mantles. Monazite occurs in yellow grains as an accessory constituent of gneiss, pegmatite, and many granites. It is obtained from alluvial deposits and mainly from sea beaches in Southern India and Brazil. The Indian is the richer and yields about 8 per cent. of thorium oxide. Owing to the smaller use of gas as an illuminant the price of monazite sand has fallen to about 3d. per lb. and the production in India from 2000 tons in 1918-19 to an average of 300 tons; the output from Brazil, which was 7000 tons per annum, has stopped.

THE GEMS

THE DIAMOND—The gems are mostly common materials, such as carbon, alumina, and earthy silicates, crystallized by contact metamorphism, or superheated steam, or acids under pneumatolytic conditions. The diamond is first in scientific and historic interest. It was found to be a crystalline form of carbon, as its ignition by a burning glass produced only carbon dioxide. The diamond is the hardest known natural substance. Its hardness led to the legend that it is indestructible unless treated with goat's blood. The chief supplies have come from the interior of South Africa, 150 million carats,[1] from Brazil, 15 million carats, from India,

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[1] The metric carat of 200 milligrams = $3\frac{1}{10}$ grains, has been the accepted standard since 1913; the former carat was $3\frac{1}{6}$ grains.

10 million carats, and from S.W. Africa, 7 million carats. Owing to its hardness and resistance to weathering the diamond is widely distributed in alluvial deposits, which were for long the only source. Brazil yielded most of the supply from 1721 till 1870.

South Africa—The first South African diamonds[1] were discovered in alluvial deposits in 1867. They were found at Kimberley in 1870, in an oval patch of a yellow ground covering the unoxidized "blue-ground" (kimberlite) which proved to be an ultra-basic intrusion. After the workings had been amalgamated into one company in 1888 deep mining became possible, and has been carried to 3500 feet. The country consists of the Upper Carboniferous Ecca shale, which rests on pre-Palæozoic quartzites and basic lava; they lie on crystalline schists, which have been intruded by quartz-porphyry and pegmatite. The diamonds are found in the blue-ground with olivine, pyroxenes, biotite, and garnet, and the largest number of mineral species found in any one rock. The kimberlite includes pseudo-spherulites similar to those formed around geysers; it was probably saturated with superheated steam, and was viscous rather than molten. The diamonds are scattered through the rock, and as some of them are broken, they were formed before its final consolidation. At Newlands, Kimberley, some diamonds were found in eclogite boulders; but 20 tons of these boulders from the Kimberley Mine did not yield a single diamond. Diamonds have been found in other igneous plugs in South Africa, but they are absent, or practically absent, from nine-tenths of the kimberlite occurrences. The Premier Mine yielded the largest known diamond, the Cullinan, which weighed 22 oz., or 3025 carats, and has been cut into 105 gems.

Brazil—Elsewhere diamonds have been derived mostly from pneumatolytic contact rocks and pegmatites, as in Brazil, India, Southern Rhodesia, and West Africa. The Brazilian diamond fields are of two different types. Diamantina in Central Minas Geraes, is a belt 250 miles long by 20 miles wide, and consists of pre-Palæozoic quartzites, schists, and pegmatites, and the overlying Diamantina Conglomerate. The diamonds occur in the conglomerate, but

[1] P. A. Wagner, *Diamond Fields, Southern Africa*, 1914.

have mostly been obtained where they have been reconcentrated in river gravel; they are associated with quartz, zircon, tourmaline, disthene, and mica; the only igneous rocks known are the pegmatites in the underlying schists and occasional pebbles in the conglomerate, and a kimberlite tuff at Uberaba, which contains no diamonds (Hussak, *Z. prakt. G.*, xiv, 1906, pp. 322-4).

The younger Brazilian deposits, the Levras sandstone and conglomerate, of Bahia, may be Carboniferous in age. The associated minerals include tourmaline, zircon, garnet, staurolite, and kyanite. No igneous rocks occur with the diamonds, which have been attributed to undiscovered dykes by D. Draper (*Mining Mag.*, ix, 1913, p. 435), E. C. Harder and R. T. Chamberlin (*Journ. Geol.*, xxiii, 1915, p. 418), and Miller and Singewald (*Min. Dep. S. Amer.*, 1919, pp. 213-4). On the other hand, J. C. Branner (*Amer. Journ. Sci.*, (4), xxxi, 1911, p. 490) regarded the diamonds as formed during the metamorphism of the quartzites, and according to O. A. Derby (*Journ. Geol.*, xx, 1912, p. 455) they were due to pneumatolytic alteration of a fractured ultra-basic rock. The mineral association suggests a pneumatolytic origin by some ascending boric acid solution.

The diamonds discovered in 1908 along the coast of South-western Africa were at first regarded as washed out of submarine necks of kimberlite. According to E. Kaiser (*Diamantenwüste Sud-West-Africas*, 1926, ii, pp. 329, 338) they came from various sources, and were collected into a sheet of sandstone, whence they were carried into Eocene and later sands. The association of these diamonds with native gold and copper, chalcopyrite and pyrite, iron and manganese oxides, garnets, zircon, sillimanite, tourmaline and topaz, does not suggest an ultra-basic igneous origin; some were probably formed in contact zones with the sillimanite, and others under pneumatolytic conditions with tourmaline and topaz. The diamonds are small; the largest found weighs only 50 carats.

The diamonds of the field on the Gold Coast discovered by Sir A. E. Kitson (*Gold Coast G.S.*, *Bull.* i, 1925, p. 35) are attributed to the action of igneous rocks on carbonaceous slates.

THEORIES OF FORMATION BASED ON SUPPOSED ARTIFICIAL DIAMONDS—The current theories as to the formation of diamonds are based on the belief that microscopic diamonds have been made artificially by the reduction of carbon at high temperatures and under great pressure in the presence of metallic iron, lithium, or basic silicates, or by the explosion of cordite in a bomb. These experiments led to the general conclusion that most diamonds were formed during the cooling of ultra-basic igneous rock and native iron. The artificial production of the diamond is however discredited by the work of Sir Charles Parsons in continuation of the researches described in his Bakerian Lecture (*Phil. Tr. A.*, vol. 220, 1926, pp. 67-107). He has examined the specimens exhibited to the British Association by Sir William Crookes, and analysed numerous specimens that he has himself made by the methods of Moissan and Crookes; he tells me that the crystals claimed as artificial diamonds are mostly silicon carbides, and other complex carbides of the impurities in the iron, viz. calcium, magnesium, chromium, etc., and that in his opinion no artificial diamond has yet been made.[1] He adds that for many years he believed the crystals, some of which he exhibited at the Royal Society in 1915, were diamonds, and that they burnt in oxygen at 900° C.; but on repeating this test with rigorous care the most characteristic crystals were found uncorroded; some few had been whitened but retained their original form.

Many facts, such as the nature of kimberlite, the matrix of the diamonds in the chief South African mines, and the presence in diamonds of hydrocarbons and apophyllite which would be decomposed at a high temperature (e.g. J. C. Branner, *Amer. Journ. Sci.*, (4), xxxiii, 1912, pp. 25-6, and G. F. Williams, *Tr. Amer. I.M.E.*, xxxv, 1905, p. 451), indicate that the diamond was not formed at a high temperature. Its geological occurrence is in favour of its formation by the slow crystallization of carbon set free by the dissociation, probably of a hydrocarbon or carbon tetrachloride at a moderate temperature, in material rendered viscous by superheated steam, as at the root of a mud volcano, or where a pneumatolytic solution is acting at an igneous contact or is producing pegmatite.

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[1] H. Le Chatelier remarks (*Science et Industrie*, 1925, p. 194), "No one believes any more in the diamond of Moissan."

Bort is a black variety of diamond, which grows in radial groups. It is used for cutting brilliants and for the dies in wire drawing. Carbonado is a massive black diamond, which has no cleavage, and is therefore tough as well as hard; it is found in pieces up to 3000 carats in weight; it was used for the cutting rims of core drills until the rise in price led to its general replacement by cutting bits of iron or steel, and by chilled shot.

THE CORUNDUM GROUP

The gems of the corundum group consist of oxide of aluminium (Al_2O_3). Their value depends on their colour as they lack the brilliance of the diamond. They crystallize in the hexagonal system, their hardness is number 9 on the scale, and they have no cleavage. Corundum crystallizes from a magma that contains an excess of alumina as quartz does from an excess of silica. Corundum is formed mostly with basic calcic rocks because in those rich in alkalis most of the alumina is used as felspar; spinel is formed in those rich in magnesia, and the alumina left is available for corundum. Morozewicz (*Tsch. Min. and Pet. Mitt.*, xviii, 1899, pp. 190-1, 240) showed that a nepheline-basalt when fused with glass dissolves alumina and throws it out during cooling. If the magma cool rapidly, as in dykes, the corundum may be distributed throughout the rock, but in slowly cooling masses it forms on the margin. Hence corundum in commercial quantities forms where an ultra-basic rock is intrusive into rock rich in alumina. Thus the corundum mines of North Carolina occur where dunite (Pratt and Lewis, *N. Carol. G.S.*, i, 1905) intruded gneiss, and the dissolved alumina crystallized on the margin in an irregular sheet or pockets of corundum.

Sapphire, the blue variety, has been formed in scattered crystals beside narrow intrusions of basalt in New South Wales (Curran, *J.R. Soc. N.S.W.*, xxx, 1896, p. 235), in Mull (*Mem. G.S. Scotl.*, Mull, 1924, p. 274), and Montana (Pirsson, *Amer. J. Sci.*, (4), iv, 1897, p. 42). Most sapphires come from alluvial deposits in Ceylon and are doubtless derived from deep-seated contacts.

The most valuable variety is the ruby, which is red and may be worth £300 a carat; it is mostly mined from a metamorphic pre-Palæozoic limestone in Upper Burma.

Some varieties are named after gems of the same colour; thus the green is the "oriental emerald," the yellow the "oriental topaz," and the violet the "oriental amethyst." The star-ruby and star-sapphire have six rayed series of inclusions. The impure massive form of corundum, emery, is of great value as an abrasive. Large crystals of opaque corundum are found in metamorphic contact zones, and are used for the bearings in instruments, etc. The ruby and sapphire are now manufactured by the fusion of alumina.

Emerald—The emerald—the precious variety of beryl ($Be_3Al_2(SiO_3)_6$), a beryllium aluminium silicate coloured by chromium—is emerald green. It crystallizes in hexagonal prisms, has the hardness of 7·5 to 8, and sp. gr. of 2·63 to 2·8. It usually occurs in pegmatites, mica-schists, and altered limestones. Some beryls in pegmatite are among the largest known crystals and weigh a ton each. Emeralds in ancient times were found mostly in Upper Egypt. In recent years the supply has come from slate in Colombia, from mica-schist in Siberia, and from pegmatite in North Carolina and New South Wales.

Topaz—Topaz (a fluosilicate of alumina, $(AlF)_2SiO_4$ rhombic; hardness, 8; sp. gr., 3·4 to 3·6) crystallizes in long rhombic prisms, which are traversed by basal joints. When pure it is colourless, but it is typically yellow; it has been formed where gneiss, schist, and granite have been acted upon pneumatolytically by fluoric acid. It is generally associated with tin ores. The gems mostly come from the Ural Mountains and Brazil.

Zircon (ZrO_2, SiO_2, silicate of zirconia; hardness, 7½; sp. gr., 4·2 to 4·8) is second in brilliancy only to the diamond, for which it has often been mistaken. It has been called jargon owing to its variable colour, and varieties are known as hyacinth and jacinth. Zircon is a common constituent of granite and syenite, and as it is extremely resistant to weathering it is one of the commonest minerals found in the heavy residues of sands and sandstones.

Jade, a mineral of value from its translucency and coolness to the touch, includes two species. Nephrite, the green jade of New Zealand and Siberia, is a variety of amphibole, of the hardness of 6½ and a sp. gr. of 3·0. Jadeite, a pyroxene, is cream coloured and is highly valued in China; it is found in Southern China and Burma; its hardness ranges from 6½ to 7, but it is most conveniently distinguished from nephrite by its sp. gr., which is 3·3.

Lapis lazuli is a mixed mineral of rich blue colour, and consists of an aggregate of hauyne, diopside, amphibole, mica, and pyrites.

Garnets—The garnets include many species, which crystallize in the cubic system and have a dodecahedral cleavage, and are double silicates of alumina, iron or chromium, with lime, magnesia, manganese or iron. (Hardness 6½ to 7; sp. gr., 3·2 to 4·3.) The chief garnet used as a gem is the ruby-red pyrope, a silicate of magnesia and alumina; it is common in the South African diamond mines, and is known as "the Cape ruby". A brilliant emerald green garnet, andradite, from the Urals is known as the "Ural emerald." Carbuncle or almandine is the iron-alumina garnet. Cinnamon-stone, of a cinnamon-brown colour, is the lime-alumina garnet, and is found in altered limestones, as in Ceylon. A small green garnet from the Urals, which is used in sprays of colour and called olivine, is the lime-chromium garnet, uvarowite.

The garnets are generally formed as metamorphic products, and are common in schists, gneisses, and crystalline limestone.

Olivine in clear transparent varieties is used as a gem under the name of peridot.

Opal is a common cryptocrystalline form of silica. Some varieties which are iridescent from the interference effect of minute internal surfaces, are of value as gems. The chief supply now comes from Cretaceous sandstones in Australia. Its origin by replacement is shown by the existence of shells and bones composed of precious opal. Some opal was formed in the fissures of igneous rocks, where shrinkage during cooling has continually strained the veins and produced the interference effect.

The filling of cavities and replacement of irregular nodules in a rock by silica produces agate, which often shows its formation in successive layers by its banded structure. Silica stained of different colours forms the varieties cornelian, onyx, jasper, etc.

CHAPTER XIII

CLAY

ESSENTIAL PROPERTIES OF CLAY—Clay is the typical member of the argillaceous rocks (Latin, *argilla*, clay). The best-known property of clay is its plasticity when moist, and the name appears to come from the same root as clog. The essential characteristic of clay (cf. p. 191) is the size of its particles, which are not more than one five-thousandth of an inch (·005 mm.) in diameter. As explained on page 191 the distinction between sand[1] and clay is physical and not chemical.

The plasticity of clay is not fully understood. It has been attributed to chemical composition, though a sand may be made plastic by being finely ground without any change in composition; to water, but materials that are identical in water content vary in plasticity; to the shape of the particles, but either the elongated or globular form are regarded as favourable to it (Ries, *Clays*, 1906, pp. 97, 99); and to the presence of a colloid (H. E. Ashley, *U.S.G.S.*, *Bull.* 388, 1909, pp. 42, 59). The plasticity of clay has no single cause, but is due to various factors, such as a colloid or very fine particles in the interstices, which allow movement between the particles, and act like water in quicksand. The shape of the particles naturally has some influence.

Common clay is made by the breaking up of rocks and the deposition of the finer particles as a bed. Clay usually contains grains of silica in a base of silicate of alumina, with small amounts of carbonate of lime and an iron compound. The main industrial value of clay depends upon the fact

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[1] For British and important foreign sands and their economic factors, see P. G. H. Boswell, *British Resources of Sands used in Glass Manufacture*, 1918, which includes an account of sands used for most other purposes.

that heat melts some of the constituents, the fluxes, which, on re-solidification, cement the rest into a compact material. Clay may be thus burnt into brick, earthenware, or porcelain. In ordinary brick clay the fluxes are usually alkali from a felspar, carbonate of lime, and oxide of iron; they fuse at a moderate temperature. Common brick is therefore made with a low expenditure of fuel, but will not withstand a high temperature. A good brick clay contains about 45 per cent. of silicate of alumina, 35 per cent. of silica, 3 to 6 per cent. of iron oxide, 3 to 8 per cent. of carbonate of lime, 1 to 4 per cent. of magnesia, 3 to 6 per cent. of potash and soda, and 4 to 6 per cent. of water. Bricks made with more silicate of alumina shrink too much in burning, and those with more silica are too brittle. The red or yellow colour depends on the iron oxide present.

Clay with a low proportion of fluxes or a high proportion of infusible material serves as fireclay; it requires greater heat in burning, but its products withstand temperatures as high as 3400° F. The temperature in the kilns is determined by the use of "Seger cones" of various clay mixtures, which bend and melt at different temperatures.

The refractory nature of some fireclay, such as the underclay of a coal seam, is due to the alkalis having been withdrawn by the growth of plants; in others it is due to the clay particles having been washed during their deposition, and their soluble constituents thus leached out; or it may be aided, as in the Glenboig fireclay (silica 62·5, alumina 34 per cent., Fe_2O_3 2·7 per cent., alkalis and loss ·8 per cent.), by the large size of the quartz grains, which are only slightly fretted at a high temperature.

Pottery clays and the better clays used in earthenware usually consist of weathered felspathic material which is white owing to the absence of iron, and highly refractory owing to the poverty in lime and alkalis.

China-Clay—Pneumatolytic Origin—The weathering of felspar produces various amorphous silicates of alumina, such as halloysite, and some products of which the particles are so minute that they cannot be determined under the microscope, and are grouped as "clay substance."

The action of hot acids on felspar produces a crystalline hydrous silicate of alumina—kaolinite (Al_2O_3, $2SiO_2$, $2H_2O$), which when present in mass forms china-clay. It is so named from its use in China for making porcelain—a word invented by the Portuguese in support of the assertion that the material was made from the shells of a cowrie named Porcellano. One important occurrence of china-clay is at Kauling or "the high ridge" near Jao-chow Fu, S. of the Yangtze-kiang and E. of Lake Poyang; Berzelius named china-clay Kaolin under the impression that it was the raw material of this ridge. Kaolinite—the crystalline form—is only one constituent, and is isolated by washing; in Cornwall it forms on an average about a quarter of the mass. The careful washing for the finer qualities of Chinese porcelain has given rise to the statement that one man begins to wash the clay and his grandson makes the pot.

Fig. 50.—A China-Clay Mass in Cornwall.

The dotted area represents the china-clay developed in the granite (shown by short lines); *b*, a band containing biotite; *Z*, zircon crystals in the overlying soil; none were found in the china-clay. Parallel lines, slate, kaolinized near the contact with the granite. Dark lines, tourmaline veins.

China-clay in Cornwall and Devon (Fig. 50) occurs in deep blocks and pipe-like masses in granite, and it consists chiefly of quartz, white mica, kaolinite, tourmaline, and topaz. The quartz is in rounded corroded grains which from their shape and size have been compared to mulberries. The washed residue consists of a pure white clay composed of minute flakes of white mica and kaolinite. The kaolinite crystallizes in hexagonal scales which have a highly developed basal cleavage, and are very similar to muscovite mica. The tourmaline is of the black variety, schorl, and occurs in scattered crystals or in veins which may extend into the granite and are then bordered by china-clay. Small crystals of topaz are common; flakes of biotite remain where it was present in the granite; and fluor-spar is conspicuous where the granite contained a lime felspar. Cassiterite is generally present and many of the china-clay masses were discovered by the Phœnicians and worked for tin.

The conversion of granite into china-clay was formerly attributed to the percolation downward of water containing carbon dioxide, the removal of the potash of the felspar, and the recombination of the silica and alumina as kaolinite. G. Hickling (*Tr. I.M.E.*, xxxvi, 1909, p. 21) regards the kaolinite as formed from altered mica. The formation of the kaolinite by weathering, though adopted by W. Lindgren (*Min. Dep.*, 1913, p. 305) is invalid for English china-clay. If it were due to the water containing carbonic acid the accessory minerals should include carbonates; they are however compounds of boric and fluoric acids, and include tourmaline (a variable boro-silicate), axinite (a boro-silicate of aluminium and calcium), and topaz (fluosilicate of alumina, AlF_2, SiO_4).

That china-clay was formed by hot deep-seated acids is also indicated by minerals which are clues to weathering; for biotite, which is readily thus destroyed, remains in china-clay formed from biotite-granite, while zircon, which resists weathering, has disappeared. No zircons could be found at the Carpella Mine in Cornwall, whereas they are abundant in the soil on the surrounding granite. Further, the clay-slate or killas beside a china-clay mass, as at the Carpella Mine, often contains much tourmaline due to the entrance of boric acid. Moreover, cassiterite, the metallic mineral characteristic of deep-seated acids, is a typical associate of china-clay.

The distribution of the china-clay blocks is inconsistent with their formation by weathering. They are absent from many granites as in Scotland, and are confined in the British Isles to the roots of the Hercynian Mountains. There is no china-clay in many extensive areas of granite and gneiss in Scandinavia, although it occurs in Baltic islands that have been disturbed by the Hercynian movements; but as the kaolinization has there acted upon basic rocks such as diabase, it has produced a material commercially of little value.

R. H. Rastall (*Tr. R.G. Soc. Cornwall*, xv, 1925, pp. 415-38) suggests the formation of the Cornish china-clay by the action of steam on felspar without fluorine or boron; but the constant association of china-clay with tourmaline and topaz, and its absence from propylitic deposits due to steam combined with carbonic acid, indicates that its formation is pneumatolytic. Kaolinite is found in small quantities beside mineral veins in Anglesey. It has been formed in felspathic sandstones in Scotland and the Midlands by superheated steam and carbonic acid from dykes having kaolinized the felspar grains; this kaolinite is therefore due to pneumatohydrolysis.

GERMAN DEPOSITS OF VARIOUS MODES OF FORMATION—The German china-clays are due to two processes. Some of the most important deposits, such as those at Meissen that are used for Dresden china, are due to descending waters charged with sulphuric acid produced by the decomposition of pyrites from brown coal. These china-clays occur as superficial sheets, which pass into the country rock, which at Meissen and Baselitz (Fig. 51) is quartz-porphyry and volcanic tuff, and elsewhere the china-clay occurs where brown coal beds rest against quartz-porphyry (Fig. 52).

FIG. 51.—CHINA-CLAY.

China-clay (C.C.) resting upon and passing down into quartz-porphyry (Q.P.) at Baselitz (after Stahl).

FIG. 52.—CHINA-CLAY.

China-clay produced by the action of acids from brown coal in Bavaria on quartz-porphyry (after Stahl).

These deposits do not contain tourmaline, except where, according to Stahl, it existed in the original granite, and biotite is rarely preserved. Roesler attributes the formation of this china-clay to solutions rising through fissures; but the evidence cited by Barnitzke (*Z. prakt. G.*, xvii, 1909, p. 471) and A. Stahl (*Arch. Lag.*, xii, 1912) favours the descending movement of the acid water. Stahl has called such china-clay exogenous as due to alien waters, in contrast to the endogenous, which is due to waters acting during the original formation of the associated deposits. Some of the latter group, e.g. those of the Naab Valley in Bavaria, are due to pneumatohydrolysis, being due to ascending carbonic acid solutions which are there connected with basalt (Stahl, *ibid.*, p. 128).

The German china-clay is formed by both plutonic and meteoric waters. Those china-clay deposits in the United States that are kaolinized acid dykes may be due to meteoric water. The china-clay stocks of Victoria are associated with tourmaline, and are of pneumatolytic origin.

China-clay is used for many purposes. Its price usually varies between £1 and £2 per ton. Its most important use is for porcelain owing to its purity in colour and resistance to high temperatures. Impure varieties are used for refractory bricks. As china-clay is easily moulded, it is used for the manufacture of wall-paper with a raised surface; as it is inert and innocuous it has been used as an adulterant for confectionery and ice creams.

FULLER'S EARTH—Fuller's earth differs from clay by being usually non-plastic. It is an amorphous hydrosilicate of alumina similar to halloysite; it is very fine in grain and has the property of absorbing grease and colouring matters. It was formerly used to remove grease from wool during the process known as fulling; its main present use is for the filtration of oils, and as a constituent of paper, soap, and drugs. Fuller's earth is generally interstratified in shallow water marine deposits which often contain glauconite. It was apparently laid down under conditions in which silicate of alumina was deposited as a fine clay mixed with a little sand composed of quartz or felspar, and often some carbonate of lime. It generally contains about 70 to 80 per cent. of silicate of alumina, from 4 to 10 per cent. of ferric oxide, from 1 to 5 per cent. of carbonate of lime, from 1 to 2 per cent. of alkalis, and 8 to 25 per cent. of water. The material owes its absorptive properties to the minute size of its particles, which offer a large area for surface tension; and as the material is not plastic it remains friable so that all the surface is reached by the liquid that is being filtered. England formerly produced the largest quantity, which mainly came from a bed known as "the Fuller's Earth" in the Lower Oolite of Wiltshire. Its existence led to the establishment there of the early woollen industry. The second important English deposit is in the Lower Greensand of Nutfield and Reigate in Surrey. In America Florida earth is largely used for the discoloration of oils. The American fuller's earths are very varied in character and origin; that in Arkansas occurs in veins formed by the alteration of basalt dykes; the Bentonite of Tennessee is an altered volcanic ash; that of Massachusetts is a glacial silt.

The production of fuller's earth in England in recent years has varied from about 20,000 to 30,000 tons, and its price has been about £2 per ton.

CHAPTER XIV

BUILDING STONES AND ROAD METALS

I. BUILDING STONES[1]

BUILDING stone may appear so durable that it might be expected to last for ever; yet some stone buildings decay with deplorable rapidity. The outer stone of most of Westminster Abbey is said to have been replaced five times. The British House of Parliament, built in 1840-50 of stone recommended by a Royal Commission whose report (1839) was for long the standard text-book on British building stones, has crumbled so fast that its ornament has been partly replaced by cast-iron, and the Members of Parliament were warned in 1925 not to stand within 3 feet of the walls to avoid falling fragments. The quickness with which stones decay may be realized in any old churchyard, for it is rare to find an intelligible inscription on a tombstone more than 200 years old, unless it has been recut. Poor stone is less durable than good timber. Most of the buildings that have lasted six or seven centuries are churches, which were built by religious fraternities who would have regarded the use of inferior material as sacrilege.

CAUSES OF DECAY—The decay of building stone is primarily due to the entrance of water, which weakens or dissolves the cement and introduces material that, on solidification, disintegrates the stone. The early builders therefore designed projecting dripstones, string-courses, and gargoyles to throw the rainwater off the building. The injurious effect of moisture is often shown by the decay of the under surface of projecting stone, and in the lower part of a wall which

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[1] J. A. Howe, *The Geology of Building Stones*, 1910; for the testing of stone, J. Hirschwald, *Handbuch bautechnischen Gesteinsprüfing*, Berlin, 1912.

is not protected from the rise of water by a damp-course. The solvent effect of rain-water is mainly due to acids derived from the atmosphere. The most important is carbonic acid (CO_2); it converts the insoluble unicarbonate of lime (CaO, CO_2) into the bicarbonate ($H_2CaC_2O_6$, i.e. $CaO, 2CO_2, H_2O$), which is removed in solution, causing the crumbling of rock with a calcareous cement. The silicates of lime and of the alkalis are also converted into carbonates and removed in solution. The air of industrial cities includes sulphuric acid, as coal generally contains in pyrites more than ·5 per cent. of sulphur, and combustion of that amount produces 35 lb. of sulphuric acid per ton of coal. Building stones are also attacked by sulphuric acid derived from sulphates in the mortar which are due to pyrites in the fuel used to burn the lime. The insertion of new cement between old stones may ruin them, as carbonate of lime may be deposited in the pores and have a disruptive effect. The air receives nitric and hydrochloric acids from factories, nitric acid by the oxidation of nitrogen by lightning, and chlorides from the sea.

Common salt, sodium chloride, is introduced into the air by the evaporation of sea spray and the minute winged crystals are blown far inland. The salt is dissolved and soaks into porous stone, which it weakens as its crystallization forces the grains apart, while it keeps the surface damp by absorption of moisture from the air.

Building stones are also attacked by agencies which act mechanically. The wind often has a speed of 30 to 60 miles an hour and sometimes of over 100 miles (as in Glasgow, 28 January, 1927), and like a sand-blast it hurls against buildings sharp fragments of quartz from the road stones and jagged shreds of iron from cart wheels. Soft particles at a high speed have a cutting effect, for soft wheaten flour cats into quartz or topaz when flung against it by a sand-blast.

Sudden changes of temperature fracture rocks. When water freezes in the pores of a rock its expansion forces off "frost-flakes." The chilling of rock in a tropical desert after sunset throws off similar flakes, and sudden exposure to the sun produces insolation flakes. The freezing of water in a stone has been estimated as having a destructive effect equal to the blow of a ten-ton hammer per square inch of surface. Repeated variations of temperature in a rock of which the constituents expand unequally when heated produce cracks parallel to the surface; this "spalling" in the tropics breaks granite into thin slabs, and they peel off leaving dome-shaped hummocks. Spalling is in some countries used in quarrying; as the sudden chilling by water of a hot rock surface breaks it into slabs; their thickness varies with the treatment.

Stones are also attacked by organic agencies. Bacteria contribute largely to the decay of rock debris into soil, and they doubtless also affect building stones. A block of stone may suddenly decay at one point; if unchecked the process will spread like an infection, but it may be stopped if the decayed material be removed and the part sterilized.

TESTS OF BUILDING STONE—The test of the durability of building stone most often used is the crushing strength; rectangular blocks 2 inches square by 3 inches high, are crushed by a machine which records the breaking pressure. Weaker stones are tested in 4-inch or 6-inch cubes. The value of this test is in the main indirect, for practically all stones withstand much higher pressure than they are subject to in buildings. The crushing strength of granites is from 850 to 1300 tons per square foot; of sandstone from 200-1000 tons; of limestone from 100-1000 tons, and dolomites from 300-600 tons. In an ordinary building no stone is subject to a greater load than about 10-12 tons per square foot; the greatest load in the Washington Monument, which is 555 feet high, is only 22-26 tons per square foot. Stones that best resist crushing generally best resist weathering. The value of this test is lessened by its variability; the crushing load may vary 30 to 40 per cent. in material from the same quarry, and great variation may occur in samples cut from the same block.

The resistance to shearing, which is especially important in building material, is tested by a rod pressing against samples of a standard size of 6 inches by 4 inches by 2 inches. Granite has a resistance to shearing of from 65 to 200 tons per square foot, sandstone from 65-85 tons per sq. foot, and marble about 100 tons per square foot.

The tensile strength is usually about one-fifth of the crushing strength, and indicates durability and resistance to frost.

The specific gravity of a building stone shows its weight and its porosity, which is an important factor in durability. Porosity is often expressed by the weight of water absorbed by a stone divided by the dry weight of the stone. The test of soakage in water for 24 hours usually gives too low a porosity, as many of the pores are not filled. Soaking for a longer time or under pressure gives more reliable results. The nature of the porosity must also be considered; for a stone with open pores loses water readily and thus is less likely to be injured by frost. The former test of weakening by freezing was to boil a sample in a saturated solution of sodium sulphate, and hang it up to dry. The crystallization of the salt breaks off fragments of the stone which are washed, dried, and weighed. In Hirschwald's method a piece is thoroughly soaked with water and frozen and thawed twenty-five times during a month; the tensile strength of the stone is measured before and after this treatment and the difference is the weakening by freezing. Some rocks are seriously weakened by saturation with water, especially those with a clay cement. This quality may be tested by the ratio of the crushing strengths before and after 28 days' soaking. This ratio may vary in sandstones from ·1 to ·9, and no stone in which the ratio is lower than ·6 should be used in a damp frosty locality.

The tests of building stones have been condemned as valueless because they are little used in British practice, where architects and builders have the experience of centuries to guide them. That much value is attached to the crushing strength may be inferred from its frequent statement in trade advertisements; and tests are advisable for new stones or new conditions. Building stones which appear of good quality sometimes fail through some unsuspected weakness.

The most important practical tests are the crushing strength, the weakening of the cement by water, and the porosity. The weakening by water may be judged roughly by placing a piece of the stone in water for 24 hours, then stirring the water and observing the extent of the muddy streaks which arise from the stone. The porosity can be tested by placing a squared sample on wet blotting paper and observing the rate at which coloured water rises into it and also by determining the amount absorbed by weighing a test piece before and after complete immersion. A stone with attractive qualities may be unsuitable owing to high porosity where rain is flung against the buildings by high winds.

MICROSCOPIC EXAMINATION—PANAMA "BREAKS"—These tests should be supplemented by microscopic examination of thin sections which reveals qualities that cannot be inferred from chemical analysis or crushing strength. The method quickly determines the chemical composition of coarse-grained rock; it shows whether the felspar is potash-felspar, which is generally more durable than the soda- and lime-felspars. A bulk chemical analysis shows the proportions of the constituents; the microscope shows how they occur. For example, the Reigate sandstone, which was used for parts of Westminster Abbey, perishes in a city atmosphere, although it contains 80 per cent. of silica, for its cement is its 10 to 15 per cent. of carbonate of lime; whereas the Chilmark Stone with 79 per cent. of carbonate of lime better resists weathering because its cement of silica protects the calcareous particles.

The experience at the Panama Canal[1] shows the value of microscopic examination of stone, and that crushing strength is not always a reliable guide. The International Board of Consulting Engineers for the Panama Canal in 1906 expected, from crushing tests on bore samples, that the banks would stand at a slope of three vertical to two horizontal, and would be stable in a cutting 245 feet deep. Yet the bottom of that excavation began to upheave when the depth was only 65 feet. These upheavals, or "breaks" continued in 1912 when the slope had been reduced to one vertical to 3½ horizontal. The weight of the banks forced the underlying mudstone, after water gained access to it, to upflow into the excavation. The upheavals were sometimes fast; a heavy steam shovel was uplifted 9 feet during an afternoon, and some machinery raised 11 feet in 10 minutes; in some cases the uplift recurred seven times before all the mobile layer had been squeezed out.

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[1] *Reports of the Isthmian Canal Commission*, 1899-1911 Vaughan Cornish, *Edinb. Review*, Jan. 1913, pp. 21-42, and *Geog. Journ.*, xli, 1913, pp. 239-43.

The strength of this "argillaceous sandstone" had been over-estimated four-fold, despite the warning of the French geologists, Bertrand and O. Zurcher, who had found in preparing thin sections that water reduced it to mud.

Varieties of Building Stones—The most durable of building stones is granite, which in the stone trade includes all coarse-grained igneous rocks such as syenite, diorite, and gabbro, and sometimes even granular marble. Granite, as defined in geology, consists of quartz, white mica, and orthoclase felspar, and owes its durability to their chemical stability. Its absorption of water is very low and often less than 1 per cent. The chief trouble with granite is "spalling" or development of cracks parallel to the surface owing to the three constituents expanding unequally on change of temperature.

The basic plutonic rocks decay by weathering more readily than granite, and being heavier are more expensive to handle. The extra weight is an advantage for some uses, as in breakwaters.

Limestones are favourite building stones owing to their lightness, beauty, and ease of working. They are as a rule unsuitable for use in cities, as they decay in an acid atmosphere. The carbonate of lime on the surface may be converted into a fur of sulphate, which is easily removed and leaves another layer liable to the same change. Dolomite, being less soluble than carbonate of lime, may be more durable; but the Houses of Parliament at Westminster show that poor dolomite decays rapidly. The stone recommended for that building was used at the same date for the Geological Survey Museum, three-quarters of a mile distant, and it has lasted exceptionally well. In the Houses of Parliament, owing to the difficulty of getting an adequate supply, dolomite of very inferior quality was accepted. A subsequent Royal Commission reported that much of it ought not to have been used for building under any conditions whatever.

Sandstone is largely used in cities being less expensive than granite and more durable than limestone. The durability of sandstone depends mainly upon its cement. The best sandstones consist of quartz grains in a siliceous cement. Iron oxide cements, which colour stones red or brown, are generally stable.

A sandstone should be compact, for, if porous, the water attacks the cement, and weakens the stone on freezing. Hence the brown sandstone used in New York is rejected if it weigh less than 130 lb. a cubic foot, or absorbs over 5 per cent. of water on 24 hours' immersion, as either test indicates too high a porosity.

Slate is often a durable building material. The main source of weakness is when its iron sulphide occurs as marcasite instead of as the ordinary cubic pyrite. Slate might be more largely used, but for its dull colour.

Stone Preservation—The preservation of building stones depends mainly on preventing the entry of moisture. Paint is effective but expensive, as it has to be renewed, and removes the beauty of stonework. The exclusion of moisture is the purpose of numerous processes. Waterglass or silicate of soda fills the surface pores with silica. Sulphur dissolved in hot oil closes the pores with sulphur. The Szerelmy process uses silicate of soda containing a bituminous material. The drawback of any impermeable crust is that it flakes off owing to the expansion of the air within the stone. A coating of paraffin over the grains of the stone prevents the entrance of moisture by surface tension and yet allows the stone to breathe. The process is however too expensive for general application. A. P. Laurie has introduced the use of silicon ester (prepared by the action of alcohol on silicon tetrachloride) which deposits silica on the grains and not as a film; it leaves the pores open (*J. Soc. Chem. Ind.*, xliv, 1925, p. 91 T.).

The baryta method was designed by Church for the Chapter House at Westminster Abbey;[1] it was built in the thirteenth century of Upper Greensand from Reigate in Surrey, which is a siliceous sandstone containing grains of glauconite and cemented by from 10 to 15 per cent. of carbonate of lime. The cement has been converted by sulphuric acid into gypsum (hydrous sulphate of lime). The building was sprayed—as the stone was too friable to withstand a brush—with a solution of barium hydrate (3 per cent. of BaO in water), which converts the sulphate of lime into the insoluble barium sulphate; the calcium of the gypsum is left as hydrate,

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[1] A. H. Church, *Memoranda Concerning Treatment of . . . Chapter House . . . Parl. Pap.*, 1904, Cd. 1889.

which absorbs carbon dioxide from the air and is deposited as carbonate of lime in the interstices of the stone and thus strengthens it.

The process failed at Westminster because the decay had gone too far, and the new crust flaked away. The restoration of building stone which has undergone thorough decay has proved so far economically impracticable.

II. ROAD METALS

The suitability of stones for road construction depends on qualities different from those required in building and varies with the climate and traffic. A good road metal must be sufficiently tough to withstand the traffic; the powder formed by its wear and tear should act as a cement and form a smooth impermeable surface; and the stone and its powder should hold by surface-tension the water mixed with it, and the tar or bitumen added as binding material. The selection of road metal depends primarily upon traffic. A comparatively soft stone will carry light vehicles if its powder binds well; hence limestone, volcanic tuff and laterites, though weak and friable, form excellent country roads. Massive granite setts may be necessary to carry heavy lorries near docks and factories. For such setts hardness alone is inadequate, for a quartzite would become slippery and make a good slide but a bad pavement; rocks are used which have constituents of different hardness, such as granite, as the felspars wear more readily than the quartz, and the surface keeps rough and gives a good grip. As a rule, however, the constituents of a stone should be nearly equal in hardness.

Paved roads were built by the Romans, and are still used in China; they are suitable for pack animals, but not for wheeled traffic, as adjacent slabs inevitably settle at different levels and the fall of the wheel on to a lower slab drives it lower and may break it. Most modern roads have a surface of macadam, so called from the adopted name of its inventor; it consists of pieces of tough stone of uniform size, about 1 or 2 inches in diameter, mixed in some binding material; this layer rests upon a foundation which admits of some vibration, so that the surface is elastic and yields slightly to a heavy shock.

The stones used in macadam must be tough so as to resist compression and sudden blows. The best road metals are igneous rocks in which the constituents are intergrown, and especially those containing a fibrous or prismatic mineral such as hornblende. The pyroxenes are less useful as their grains are torn apart, and they yield more readily along the cleavage. Large felspars also break along the cleavages.

Among the best of the acid rocks are the granophyres in which the base consists of a fine-grained micropegmatitic intergrowth of quartz and felspar. The basic rocks have the advantage that being heavy, pieces are less easily displaced, though a given weight of stone covers a smaller area; those with an ophitic structure, such as dolerite, are the best.

The sedimentary rocks are usually less satisfactory as their rounded grains are easily torn out of the cement, and powdered quartz has a low cementing value. Limestone, though soft, has the advantage that its powder acts as a natural cement. Coarse gritty sandstones, such as the graywacke of the Southern Uplands of Scotland and the harder seams in the Old Red Sandstone of the North of Scotland serve as fair road metal; they are known as whin—a term given to any rock that was difficult to quarry or resisted decay into soil. The term is now often used as if applicable only to igneous rocks.

An important factor in road metal is its adherence to tar and bitumen; hence granite is unsuitable for macadam, as if overheated the cleavages open on cooling and the rock becomes friable; if inadequately heated the tar peels off and does not bind the material properly under the vibration of traffic.

Road metal is tested by two methods—abrasion against a revolving iron plate, and the attrition test, by loss of weight when road metal is rotated on a cylinder. Lovegrove's test (*Attrition Tests of Road-making Stones, with Petrological Descriptions*, by J. S. Flett and J. A. Howe, 1905), often adopted in the London district, determines the percentage of material that will pass through a sieve with spaces one-sixteenth of an inch in diameter after 16 pieces of the stone which together weigh 4 lb. have undergone 5 hours rotation, at the rate of 20 revolutions per minute, in an

11-inch diameter iron cylinder. The stones are tested both dry and wet.

The tests for road metal recommended by the United States Department of Agriculture and the Canadian Geological Survey (*Mem. G.S. Canada*, 85, 1916, by L. Reinecke and 114, 1919, by H. Gauthier) are based upon the specific gravity, the percentage of wear under attrition in a rotating cylinder, hardness measured by loss in weight when pressed against a revolving iron disc armed with coarse sand, the absorption of water by 48 hours' immersion, and toughness. The grade of toughness is tested by the height in centimetres through which a two-kilogram hammer must fall to break a cylinder of the stone, an inch in diameter and height.

According to the U.S. Office of Public Roads, stone for roads that are traversed by less than 100 vehicles a day may have a toughness of 5-9, by 100 to 250 vehicles a day of 10-13, and by more than 250 vehicles a day a toughness of 10-19, according to the different setting of the macadam.

CHAPTER XV

THE GEOLOGY OF CEMENTS

Definition and Groups of Cements — "Cements," says Desch (*Chemistry and Testing of Cement*, 1911, p. 1), "may be defined as adhesive substances capable of uniting fragments or masses of solid matter to a compact whole." The cements, excluding the organic such as glue, are mostly calcareous materials which have the property of "setting" hard. The name comes from the Latin *caedimentum*, or "chipped broken stone," and was given to a mixture of broken stone or tiles with lime; this material was really mortar, i.e. cement mixed with inert materials.

The oldest cement was probably mud, which, like the burnt calcareous material used in Egypt, would not last in a wet climate. The Greeks and Romans required cement that would withstand rain and set under water; they prepared hydraulic cement from volcanic tuff, and from use of that at Pozzuoli, a suburb of Naples, it was named Pozzolana.

After the fall of Rome the art of preparing good lime was lost until the twelfth century. Builders then began to improve mortar, but hydraulic cement was not rediscovered until 1756, when Smeaton was designing the third Eddystone Lighthouse. The cement in its predecessor had been protected from water by metal bands. Smeaton set himself to prepare a cement that would resist water and be as hard as the stones it joined; he succeeded by burning equal parts of the earthy Liassic limestones of Glamorganshire, and of volcanic tuff, known as Trass, from the extinct volcanoes of the Rhine.

Cements are divided into two main groups. In the first the action depends upon the replacement of some constituent, usually moisture or carbon dioxide, which has been expelled by heat; as it is replaced the cement becomes hard or "sets."

This group includes plaster of Paris and the lime cements. In the second group the setting is due to new compounds being formed at a high temperature or by mixing materials that are chemically unstable. This group includes hydraulic limes, Portland cement, and cements with amorphous or glassy silica.

The simplest kind of cement is prepared by burning limestone, from which at the temperature of 1400° to 1650° F., the carbon dioxide is driven off and lime left. When lime is mixed with water it slakes to the hydrate or slaked lime ($CaO + H_2O = CaH_2O_2$), which when mixed with sand forms mortar and sets firmly on drying. No chemical reaction takes place between the lime and sand, which prevents excessive shrinkage, and hardens the material. The lime absorbs carbon dioxide from the air, and is reconverted to carbonate.

Pure limestone yields "fat lime," in contradistinction to "lean lime," which is impure and earthy. Many of the older limestones have too much silica or clay to form fat lime, and the impurities fuse in the kiln into useless slag.

HYDRAULIC AND PORTLAND CEMENTS—The best known of the cements which set under water is Portland cement, which was discovered by Aspdin of Leeds in 1824, and named from its resemblance to Portland stone. He began its manufacture in 1825, and attention was called to its value by its use by Brunell in 1828 in the Thames Tunnel. Two years later experiments at Chatham proved that the same type of cement could be prepared by burning an appropriate mixture of chalk and mud from the Medway. The same materials are abundant along the Thames, which became for a time the chief seat of the Portland cement industry.

The cements which can be used under water include three groups which are not sharply defined. Hydraulic cements are made from clayey limestones containing from 13 to 35 per cent. of earthy material, usually silica, silicate of alumina, and iron oxide. The material is burnt in a kiln; at from 1400° to 1500° F. the carbon dioxide is given off; at about 1650° F. the lime begins to combine with the alumina as calcic aluminates; between 2000° F. and 2350° F. the silica combines with the lime as calcic silicate, but sufficient lime remains to slake on the addition of water.

In the South-east of England hydraulic cement was made from the London clay septaria, and was called Roman cement from the erroneous tradition that the Romans made cement from them. They consist of nodules of calcareous clay traversed by septa of calcite; their usual composition is about silica 18 per cent., alumina 3 to 5 per cent., iron oxide, 5 per cent., lime 30 per cent., and carbon dioxide 31 per cent.

Hydraulic cement passes by the reduction in uncombined lime into Portland cement, which is made from a mixture of finely ground limestone and clay; the mixture is heated to a little below its fusion point—usually to between 2600° and 3000° F.—when the materials by diffusion form new compounds. As the most important constituent in Portland cement is the tricalcic silicate, $3CaO, SiO_2$, its ideal composition is lime 73·6 per cent., silica 26·4 per cent. The constituents have to be mixed in precise proportions, and therefore soft pure materials are desirable, such as chalk and river clay.

The third group, including the Roman Pozzolana cement, are made from volcanic tuff such as the Trass of the Rhine. The glass in these tuffs is unstable and combines with lime to form silicates of lime and alumina without the use of heat. Blast furnace slag, which is also a silicate glass, and various organic materials, such as diatom earth, which consist of unstable amorphous silica, make similar cement when ground with lime.

The three types of hydraulic cement depend upon analogous chemical processes. The modern interpretation of the constitution of Portland cement was founded by H. Le Chatelier (1883, etc., and his *Constitution of Hydraulic Mortars*, New York, 1905). He regarded Portland cement as consisting of crystals of tricalcic silicate in a crystalline ground mass. Later researches show that the constitution is more complex, and is dependent upon the interaction of several lime silicates and lime aluminates, each of which has a definite composition, specific gravity, and optical properties. These artificial mineral species at a high temperature, below that of fusion, combine in solid solution and form what Törnebohm called alite and celite. Alite is a solid solution of tricalcic aluminate ($3CaO, Al_2O_3$) in tricalcic silicate ($3CaO, SiO_2$), and celite of dicalcic aluminate ($2CaO, Al_2O_3$) in dicalcic silicate ($2CaO, SiO_2$).

According to Cl. Richardson (*Eng. News.*, liii, 1905, pp. 84-5), the tricalcic silicate and aluminate of alite are decomposed by water and form an especially active lime hydrate (CaH_2O_2), which crystallizes and acts as cement. The tricalcic aluminate decomposes first and its calcic hydrate sets first. The tricalcic silicate decomposes more slowly, and its silica is deposited in the setting mass and hardens it. The celite is almost inert, so that it usually takes no part in the reaction but is enclosed in the set alite.

PRICE—The manufacture of Portland cement on a great scale began in England and it was not until about 1895 that it was largely made in the United States, which has since become the greatest producer with about 26 million tons per annum; Germany is second with 7 million tons; the British Empire makes 5 million tons; France and Belgium 2 million tons apiece. The average price from 1870 to 1880 was 12s. a barrel (380 lb. before 1921, later 376 lb.); it had fallen to 8s. a barrel by 1893; American competition and improved methods of manufacture lowered the price to 3s. 6d. in 1908; it rose at the end of the War to 8s., and in 1926 to 10s. a barrel.

GYPSUM CEMENTS—PLASTER OF PARIS—Plaster of Paris is a cement made from gypsum ($CaSO_4$, $2H_2O$), which when pure consists of 79·1 per cent. of sulphate of lime and 20·9 per cent. of water. Alabaster is the white fine-grained variety used for statuary; selenite is the water-clear crystalline variety.

Primary gypsum, due to the evaporation of sea-water, often occurs as beds or lenticles interbedded in red shales or marls. Gypsum, formed by the hydration of anhydrite ($CaSO_4$), has disturbed and slicken-sided margins owing to its expansion.

Gypsum occurs in veins, in irregular pockets traversing calcareous rocks, as a limestone-gypsum breccia, and in masses in contact with corroded surfaces of limestones, which, to use J. V. Harrison's phrase, look worm-eaten. Such secondary gypsum is due to the decomposition of pyrites having produced sulphuric acid, which has invaded limestone and altered the carbonate into sulphate. The process happens on a small scale in clay and forms selenite in crystals, nodules, and casts of shells. This explanation was adopted by Dana (1871, *Manual of Geology*, p. 248) for gypsum deposits in

New York; by L. H. Cole (*Gypsum in Canada*, *Can. Dept. Mines*, 1913, pp. 94-99) for those in British Columbia; by G. E. Pilgrim (*Mem. G.S. India*, 1908, xxxiv, p. 104), and by J. V. Harrison (*Econ. Geol.*, 1924, p. 270) for the gypsum of Persia, and by Murray Stewart (*Rec. G.S. India.*, 1919, l, pp. 63, 67) for that of the Salt Range of the Punjab.

The setting of gypsum is a delicate process requiring careful control of the temperature and amount of water, as too much leaves the crystals loose and the plaster friable. The water present should be not more than about a thousandth of that required to dissolve the material. The temperature in burning plaster of Paris should not rise above 260° F., at which the dihydrate ($CaSO_4$, $2H_2O$), is converted into hemihydrate ($2CaSO_4$, H_2O); it readily dissolves in water, forming a supersaturated solution and crystals of dihydrate. Their formation sets free water, which dissolves more hemihydrate; it releases more water as it crystallizes into dihydrate; and thus a small excess of water works through the material until all has set.

The value of plaster of Paris in preparing casts and ornamental mouldings is due to its expansion on solidification, so that the material is forced into the smallest crevices of the mould. The burning of gypsum mixed with alum or borax at 400° F. produces "hard plaster."

CHAPTER XVI

THE SOIL

Definition and Function—The soil is the layer of decomposed rock material charged with organic matter which covers most of the surface of the earth. It forms the basis of vegetation as it can be penetrated by roots and holds stores of plant foods. The study of soils reveals the causes of their fertility or sterility, and has enabled large tracts of useless desert to be rendered of high fertility. The soil is usually brownish or black, and from 6 inches to 2 feet in thickness; it passes into the underlying rock through the partially decomposed layer, the subsoil—a term however used in civil engineering and public health for the general foundation of a district.

Soils are of two chief classes, " sedentary soils " due to the weathering of rock *in situ*, and " transported soils " composed of materials that have undergone disintegration elsewhere. The decay of rock into soil is due to changes of temperature which break rock to pieces, solution by soil waters, oxidation, the burrowing of animals, the disruptive action of roots, and the solvent action of organic products. The main function of the soil is to convert the inorganic constituents of the air into plant tissues which can be used as food by animals. A soil is also a reservoir of plant foods, which in some circumstances may be its main value, for the deep soils of Manitoba, which contain 20 per cent. of organic matter, can produce wheat for a long period without exhaustion; but if a soil be worked simply as a store of plant food, it must be ultimately ruined.

The value of a soil may depend on accidental circumstances, such as proximity to a market, local supplies of cheap manure, and freaks of fashion, which render profitable the growth of fruits which are out of season. The essential value depends on composition, texture, porosity, and colour.

Soil Constitution—Sand, Clay, and Silt—A bulk chemical analysis of a soil may be of little agricultural significance, as much of the material is not available as plant food. The constitution is often more instructive; it is determined by mechanical analysis, which after rejecting the pebbles, divides the material that will pass through a sieve with holes $\frac{1}{12}$-inch in diameter into sand, silt, and clay. Sand has often been regarded as composed of silica, and clay as composed of silicate of alumina; but some sand is composed of carbonate of lime, or of grains of felspar, and some clay consists of quartz ground as fine as flour. That the difference between clay and sand is physical and not due to composition is shown in mining. An ore is crushed to allow the extraction of its metal, and sorted into a coarse grade (above ·04 mm.) "the sand," and a finer, "the slime," which is a clay. Their chemical composition is identical, and the difference is due wholly to the size of the particles.

Sand is loose material in which the particles vary from $\frac{1}{25}$ to $\frac{1}{500}$ of an inch (or 1 to ·05 mm.) in diameter.[1] Clay is material in which the particles are less than $\frac{1}{5000}$ of an inch (·005 mm.) in diameter. Material intermediate between sand and clay is known as silt. Clay of less than ·002 mm. in diameter is a colloid and its effects on soils are independent of its chemical composition; colloids absorb from solutions materials that would otherwise be carried away by drainage; they strengthen the imbibition (cf. p. 228) and control the reaction of the soils to lime. Lime may act differently on two soils of the same chemical composition, since it coagulates colloids into larger particles, and thus improves the texture, and confers no such benefit upon the coarser particles of silt. A sandy soil is said to be "light," as it is friable and easily worked. A soil with more than 40 per cent. of fine sand cakes after rain, and has to be broken by rolling. A soil with 40 per cent. of sand and less than 5 per cent. of clay is rarely useful unless stable manure is abundant and the water conditions favourable. Many good loams hold less than

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[1] For a classification of the grades, and literature, see Tyrrell, *Principles of Petrology*, pp. 190-1. For methods see Boswell, *British Refractory Sands*, 1918, pp. 18-28.

4 per cent. of coarse sand. Clay is "heavy," as it is hard to work, and is often left as grassland; it shrinks during droughts and the cracks tear across the plant roots; and clay breaks into rough clods which are difficult to cultivate. Lime makes a clay soil looser and more tractable.

Soil Composition—Chemical analysis of soil determines its supply of plant foods. The four chief elements which plants obtain from the soil are nitrogen, calcium, phosphorus, and potassium.[1] Calcium is usually present in the soil as carbonate, but may be added as gypsum, the sulphate. Its chief functions are to coagulate colloidal clay, and to neutralize the acids and thus cure "sourness."

Phosphorus is used by plants as phosphoric acid, P_2O_5, and average English soils have about ·1 per cent. or up to ·2 per cent. of it, with about a third more in the soil than in the subsoil. The prairie soils of the United States have a similar excess. Thus in Illinois the average percentage of phosphorus is ·161 per cent. in the uppermost inch; ·149 per cent. for the depth of 2-3 inches; ·143 per cent. for 4-6 inches and ·127 per cent. for 7-12 inches (Alway and Rost, *Soil Science*, ii, 1916, p. 495). The Australian soils are poor in phosphorus—the average of many clay soils of Victoria is only ·047 per cent.—and it is often lower in the soil than the subsoil; this abnormal feature is probably due to the absence of ordinary mammals, whose litter of bones and dung in other continents have enriched the soil with phosphate.

Potassium, in the form of potash (K_2O), is an essential plant food and prevents some diseases. It is usually derived in soils from potash felspar.

The other essential inorganic elements of soil are magnesia—which is injurious if in excess of the lime as in some basic igneous rocks that yield surprisingly poor soil—iron, aluminium, chloride, and sulphur. Chlorine is chiefly present as sodium chloride, which is present in all soils; most crops can tolerate ·25 per cent. in the soil, while the vegetation of salt marshes is adapted to a high percentage. Sodium carbonate is very injurious except in small amounts. Few plants withstand more than one part in 1000, and owing to it much land has been ruined by ill-managed irrigation.

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[1] For the effect of the different constituents on plant growth, see Sir E. J. Russell, *Soil Conditions and Plant Growth*, 5th ed., 1926.

The Ghirriya, the northern part of the Nile delta, was in Roman times the Garden of Egypt, and produced the rice that fed the slave populations in Rome and in the Serbian mines; when the administration of Egypt was undertaken by Britain in 1883 the Ghirriya was a barren waste owing to the accumulation of sodium carbonate in the soil. This salt was removed by successive washings by the Nile floods, and the ground was restored to its former fertility. Some of the low land in Mesopotamia is faced with a greater difficulty, as the slope to the Persian Gulf is too slight to remove the irrigation water and its removal by evaporation leaves a residue of sodium carbonate.

Nitrogen, the most important organic constituent of soil, occurs mainly as a constituent of humus, which gives most soils their brown or black colour. Humus is due to bacteria, which prevents the organic matter being decomposed into carbon dioxide; as that change takes place most quickly with an excess of air humus is less abundant in light porous soils than in clay. The amount of organic matter may be as much as 20 per cent. in virgin soils, while it may be almost absent from sandy soils in the tropics where the humus is decomposed in the dry season.

Knowledge of the chemical composition of the soil enables agriculture in some cases to be managed with the precision of an industrial operation, as the material removed in each crop can be replaced in fertilizers. In general farming, however, this knowledge proved less useful than was expected. An average English wheat crop withdraws from each acre about 50 lb. of nitrogen, 20 lb. of phosphoric acid, and 30 lb. of potash. Ordinary soil has enough nitrogen to supply this amount for 50 crops, enough phosphorus for 120 crops, and potash for 70 crops. Only, however, a small fraction of these constituents can be withdrawn by the plants; and then the soil requires rest until more has become available as plant food. Efforts to distinguish between the total and available amounts have been made by treating soil with a weak organic acid; but this test does not fully overcome the difficulty, as the clods are not penetrated by the soil waters, whereas during an analysis the solvent is brought into contact with all the particles.

Soil Texture and Water Capacity—Mechanical analysis is attended by a corresponding difficulty as it deals with powdered soil which does not indicate the actual texture. Heber Green, and Ampt (*J. Agric. Sci.*, iv, 1911, pp. 1-24) have shown that the essential factors can be determined and expressed by formulæ which indicate the amount of pore space, the permeability to air and water, and the capillarity. This method represents the facts for a soil as it is, and not when it is artificially broken up.

The texture of soils controls their fertility in various ways. Soils may be barren owing to the absence of water, which drains away quickly from coarse sands; or to its excess in water-logged clay; or to deficiency of air in stiff impenetrable clay; or to acidity due to absence of carbonate of lime.

The water capacity of soil depends on its interspaces or pores. The pores in stiff clay amount to 50 per cent. of the bulk, and the total surface of the particles is about 3 acres per cubic foot. A coarse sand, on the other hand, has a pore space of only from 25 to 30 per cent., and the surface area per cubic foot is about half of an acre. As water spreads through soils in a film covering the particles, the larger their surface the more water the soil will hold. Hence clay absorbs more water than sand, and holds it more firmly. A clay soil may hold an excess of water, and being water-logged, air is excluded, and the soil is barren. A sand on the contrary may be drained quickly and may not hold sufficient water to feed a crop during dry weather. Clay may be relieved of the excess of water by drainage, which allows air to enter and aerate the roots, lightens the soil by washing away clay particles, and renders it warmer by avoiding the chilling process of evaporation. The soil is nourished from the water-table (cf. p. 224) during drought as the film of water spreads from particle to particle. The water rises higher through fine grained rock with numerous pores and uniform closely packed grains than through loose coarse material. Hence crops separated from the water-table by a few feet of coarse gravel may perish from drought; while the soil above an even-grained rock may be well-nourished.

The principle of dry farming is to till the land so that the evaporation of water from the surface is kept under full control, so that none is wasted and the crop is supplied at the right time. The loss of water and chilling by evaporation are prevented by a "mulch" or loose cover of farm refuse, or by so hoeing or harrowing the soil that it serves as a mulch. The dry farmer keeps the surface broken after every fall of rain until sufficient for a crop has soaked underground. He then rolls the ground so as to connect the surface with the water-table, so that the plants may be nourished. This method was practised in early times and its adoption has extended wheat cultivation in Australia, beyond the former supposed limit of "Goyder's Line," which marked the edge of the area with a rainfall of 14 inches.

The colour of soils affects their earliness. A black soil, such as the chernozen of Russia, and the black cotton soil of India, absorbs more heat and is warmer than a pale soil. The Indian black soils are coloured by a colloidal silicate of iron and aluminium containing some organic matter (Harrison and Swan (*Mem. Agric. Research Inst., Pusa*, No. 5, 1913). Some black soils, such as those of the highlands of Benguella, though apparently promising, are infertile, because they consist of coarse quartz grains coated by a thin film of colloidal silicate. Other black soils, such as those of the lava plains of East Africa, are darkened by the high proportion of iron and humus; they are chemically rich, but are difficult to work as the clay in the rainy season becomes semi-fluid. It is then impassable to wheeled traffic and horses. In the dry season the soil shrinks and a network of deep cracks tears across the plant roots and allows the water to sink deeper and thus increase the depth with these inconvenient properties.

Soil Composition and Surveys—Agricultural chemistry in its early days formed exaggerated expectations of the help it could give the farmer; recognition of the limitations of soil analysis led to the view that the biological factors are most important. The most accurate test available of them is nitrification; but, as pointed out by Burgess (*Soil Science*, vi, 1918, pp. 449-62), it does not explain the differences in soils or indicate how poor soils can be improved. The address by Dr. Crowther, an agricultural biologist, to the British Association in 1923, shows the return to greater faith in soil composition; he expressed the "conviction that soil investigation is the most fundamental of all forms of agricultural research." The interpretation of chemical analyses requires allowance for climate, economic position, and biological factors.

Climate may be especially important. If, e.g. the rainfall belts trend N. and S. and the rocks E. and W. the variations in rainfall may be the most influential factor (cf. Alway and Rost, *Soil Science*, i, 1915, p. 406).

The most extensive soil surveys have been made in the United States, where by the end of 1912 they covered over 520,000 square miles, or 330,000,000 acres ("Soils of the United States," *U.S. Bur. Agric.*, 1913). The soils are classified primarily according to texture, into clay, sand, sandy loam, and loam, and divided into over 1700 soil types based largely on climatic factors. The objects of a soil survey are to show the agricultural resources of a district, to provide a basis for the scientific investigation of soil, to lead to its improvement and most suitable employment, and to enable local agricultural advisers to give cultivators reliable advice. Mosier and Gustafson (*Soil Physics and Management* 1917, pp. 117-18) conclude, " If the work cease with the mapping of the soils, very little of real value is accomplished, as the soil survey is only preliminary to a more complete investigation. If, however, the soils are analysed, field experiments carried on, reports published giving the results of the work, and recommendations for improved management made, the farmer may avail himself of all this information for improving his soil and his farm management generally."

Soil survey of transported soils has been undervalued owing to their irregularity. But sedentary soils have as sudden variations. Rocks composed of thin bands or lenticles of clay and sandstone give equally patchy soils. Some drift areas have a remarkably uniform soil over hundreds of square miles. Whether the soils are too irregular for a survey to be useful has to be decided independently in each case. The soil mapping of drift areas should not be debarred by a general rule.

CHAPTER XVII

MINERAL FERTILIZERS—NITRATES AND PHOSPHATES

NITRATES

CHARACTERISTIC OF ARID AREAS—Minerals that are readily soluble in water only occur in large quantities in arid climates. Nitrate of soda ($NaNO_3$, Chile saltpetre), which is of great service as a fertilizer, is practically restricted to the almost rainless belt in Northern Chile and Southern Peru.

Nitrogen is essential to the growth of most organisms, which are dependent on the few plants that by their nitrifying bacteria can extract it from the air. The volcanic eruption on Krakatoa in 1883 destroyed all its vegetation and soil. The first plants to resettle on the island were those that use atmospheric nitrogen, and until they had enriched the soil with nitrates no other plants could live there. The rotation of crops, the basis of scientific agriculture, depends on the restoration of nitrogen to the soil by a leguminous crop. Nitrogenous fertilizers release ordinary plants from their dependence on those which extract nitrogen from the air.

The nitrate fields of Chile lie on a plain, the "pampa," between the Coast Ranges and the main chain of the Andes, in a belt 450 miles long, between 19° and 27° S. lat., between 200 and 5000 feet above sea-level, and from 16 to 90 miles from the sea. The Coast Ranges consist of pre-Palæozoic gneiss and schists; the Andes are built of Palæozoic and Cretaceous sediments and Kainozoic igneous rocks. The area is one of the driest in the world. In some places a decade passes without a single fall of rain; in others there may be a few light showers every year; at Antofagasta after several dry years a heavy shower happened in 1910, two days of heavy rain fell in 1911, and more in 1912. The coast towns were provided with fresh-water by sea, and sold at the price of often 5 gallons for a penny.

The nitrate may be recognized by its inflammability on burning wick. According to tradition the deposits were discovered owing to the ground catching fire; the alarmed Indians took some to a priest to expel the evil spirit, which he recognized as nitrate. In the eighteenth century it was used instead of saltpetre (KNO_3) for gunpowder, but the modern trade dates from the discovery by a Scottish settler near Iquique, that the white soil made his garden extremely fertile. He sent some to Scotland where its nature was determined, and the first nitrate works were established at Iquique in 1826. In 1830, 8300 tons were exported; the amount increased to 2¾ million tons in 1913, fell to 1 million tons in 1922, but had risen to 2½ million in 1925.

The nitrate deposits or "saltreras" are generally on the edge of salt pans or "salares." The sequence of deposits is usually as follows. At the surface are a few inches of decomposed "porphyry;" below is a conglomerate which is cemented by sulphates of lime, potash, and sodium, with a little sodium nitrate; next a layer of sand and clay containing salt and anhydrite. This layer and the conglomerate are together from 1-3 feet in thickness; and beneath them is the caliche, the main bed of sodium nitrate; it varies in thickness from a few inches to 6 feet; the average of nitrate in the material mined is between 20 and 30 per cent.; and less than 17 per cent. usually does not pay. The caliche rests upon sand and clay containing salt and gypsum, below which may be a second nitrate layer, the banco.

THEORIES OF FORMATION—The origin of sodium nitrate has given rise to an unusual variety of hypotheses. It was attributed to the decay of seaweeds and fish in an arm of the sea which had been raised above sea-level (Darwin, 1846, *Geol. Observ. S. Amer.*, Chap. III; C. Noellner, *J. prakt. Chem.*, cii, 1867, p. 461). The main argument for this theory was the presence of marine shells, and it was discredited when they were found to be derived from the underlying Cretaceous rocks. According to a second theory the nitrate was derived from guano, either deposited by birds on the shores of lagoons (Penrose, 1910) or blown inland from the coast (Ochsenius, 1888, *Z.d.g.G.*, xl, pp. 153-65). A third theory (W. Newton, *Geol. Mag.*, 1896; Singewald and Miller, *Proc. Soc. Pan-Amer. Sci. Congr.*, viii, 1917, pp. 873-80) attributed the nitrate to bacteria, and its concentration to solution by groundwater which washes nitrate out of the soils on the Andes and deposits it where the water evaporates on the western edge of the pampa. This groundwater would also deposit common salt in the saltpans; but, owing to its greater solubility the nitrate would be deposited separately on the edge of the salt beds.

The nitrate has been assigned also to volcanic action by the discharge of steam containing ammonia, to lightning during thunderstorms (Semper, 1893, and later Krull), to herds of llama and alpaca (O. Kuntze, 1895), and to the bodies of the extinct Mastodon and Megatherium (Plagemann, 1905).

The field relations of the nitrate show that it was deposited as an efflorescent salt by the evaporation of groundwater. Much of the nitrate may be derived from guano; for the salares appear to have been salt lakes that would have been frequented by many birds, and the nitrate from their droppings would have been dissolved and carried into the subsoil after rain or by the floods that occasionally sweep over the country from the Andes. The climate appears to have been moister during the formation of the nitrate than it is now. In dry seasons the nitrate would have been collected at the surface and deposited on the evaporation of the groundwater. Subsequently on the desiccation of the country and disappearance of the lakes and birds the supply of guano would have ceased, and the beds above the caliche would have been cemented by sulphates with occasional patches of nitrate.

The absence of phosphate may appear inconsistent with the origin of the nitrate from guano; but as phosphate is less soluble it would not have been concentrated in the caliche.

The estimates of the reserves of the material vary from 70 to 200 million tons. The supply may be expected to last, at the present output, for at least 35 to 40 years. According to Cuevas, it will last for 300 years (*Proc. Soc. Pan-Amer. Sci. Congr.*, viii, 1917, p. 62). The industry has been seriously affected by the competition of artificial ammonia, cyanamide, and calcium nitrate. Moreover, as nitrates are indispensable for high explosives most nations will probably manufacture them, so as to be independent of an imported supply.

PHOSPHATES[1]

VALUE AND USE OF PHOSPHATES—Phosphate of lime is a much scarcer mineral than carbonate of lime; it is of high importance as a fertilizer, being especially useful in the growth of grain. Burnt bones had long been used in China as manure, and their value is explained by Gähn's discovery in 1769 that bones contain phosphorous; but as bone phosphate is insoluble the fertilizing effect of bones was attributed to their gelatine, until in 1843 experiments by the Duke of Richmond showed that ground bones with and without their gelatine were equal in fertilizing value. Normal phosphate of lime ($Ca_3P_2O_8$) is insoluble; but it was discovered by Lawes in England and by Liebig in Germany, that the action of sulphuric acid on bones and mineral phosphate converts them into superphosphate or acid phosphate ($CaH_4(PO_4)2$, H_2O) which is soluble and usable as plant food. The exhaustion of many wheat fields in North-western Europe about that date led to fears of famine. Beds of phosphatic nodules occur in the S.E. of England, and their conversion into superphosphate rendered them available for the refertilization of the European grain-fields. Emerson, the American philosopher, suggested that spendthrift agriculture might be saved by agricultural chemistry "offering by a teaspoonful of artificial guano to turn a sandbank into corn;" while Liebig, with generous enthusiasm, declared that England had in its mineral phosphates, a source of wealth equal to its coal-fields. The supply of English phosphate was disappointingly small, and the industry became dependent upon imports from warm temperate and tropical regions.

The commercial phosphates are due to the concentration of phosphoric acid by various processes (Fig. 53).

The primary source of the phosphorus is the apatite in igneous rocks. It is a tricalcic phosphate of lime ($Ca_3P_2O_8$),

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[1] A general account of the geology of phosphates has been given by the author, *Tr. G. Soc. Glasgow*, xvi, 1917, pp. 116-63.

combined with a molecule of either calcium fluoride in fluor-apatite, or of calcium chloride in chlor-apatite, or of lime in voelckerite, a species named by A. F. Rogers in 1912 after the agricultural chemist who established its existence. Apatite is usually present in igneous rocks to the amount of about 6 parts in the thousand, or about ·1 per cent. of phosphorus.

Apatite Veins—Apatite may be dissolved from deep-lying rocks, and when the solution cools near the surface the phosphate of lime is deposited in pockets or veins. Some apatite veins have been regarded as igneous dykes such as those near Ottawa in Canada and the Nelsonite "dykes" in Virginia. The apatite veins in gneiss near Ottawa are of pneumatolytic origin and due to deep-seated solutions of phosphoric acid. That the Nelsonite (an apatite-ilmenite rock) in syenite and gneiss in Virginia is not intrusive is held by G. R. Mansfeld (*Phosph. Res. U.S., 2nd Pan-Amer. Sci. Congr.*, viii, 1917, p. 731).

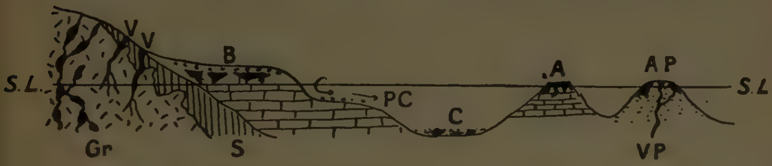

Fig. 53.—Phosphate Formation.

Diagrammatic section illustrating phosphate formation. The phosphate is black. Gr., granitic rock with phosphatic masses associated with pegmatites; V, apatite veins in granite and in slate, S; B, beds with bones and coprolites, from which the underlying limestone is converted to phosphate; PC, granular phosphate, giving rise to phosphatic chalks and granular phosphates by concentration by ocean currents, represented by the arrows; C, concretionary phosphate formed on sea floor; A, coral island with limestone phosphatized from guano; AP, volcanic island wlth banks of guano which form aluminium phosphate; VP, volcanic pipe; SL, sea-level.

Guano—The organic formation of phosphate depends on the destruction of apatite by weathering and the removal of its phosphoric acid by rivers to the sea. Some marine animals, such as crabs and the Brachiopod, *Lingula*, secrete shells of phosphate of lime. Phosphoric acid is also extracted from sea-water by minute plants and animals; they are the food of larger creatures, which are eaten by still larger, until this chain of death concentrates phosphorus in the bodies of fish, which are in turn the prey of gluttonous sea birds. Small islands off the coast of South America are the nesting places of vast flocks of a cormorant, *Phalacrocorax bougainvillei*, which weighs 6 lb., but will eat 3½ lb. of fish at a meal, and from 8 to 10 lb. in a day. They cannot assimilate all the phosphate and it is deposited in their droppings as guano—the Spanish word for dung.

The fertilizing value of guano depends also on its nitrogenous constituents, mostly ammonia, which may be washed out by rain, leaving the residue as phosphoric or leached guano. Thick guano deposits can only accumulate on islands where birds can nest safe from mammals and snakes, and in climates with an insignificant rainfall. These conditions occur off the western coasts of South America, in "Guano Islands" off South-western Africa, and in the Abrolhos Islands off West Australia, where the prevalent westerly winds pile water against the coast and cause a cold northward flowing current. The Humboldt current along South America is 29° cooler than the adjacent water, and the Antarctic fauna—fur seals, petrels, and penguins—ranges northward into the tropics. The wind that blows across this cold water has its temperature raised on reaching land and its capacity for carrying moisture thereby increased; hence the sea wind has a parching effect until the air is chilled by rising up the mountains, where its moisture falls as rain.

The supplies of guano are to some extent renewed, but the birds have at times suddenly abandoned the islands, as in 1911 when millions of the young were left to die. Dr. H. O. Forbes explained their disappearance as due to fright at an earthquake shock. They began to return three months later, and Forbes estimated that 5,600,000 of them were nesting on the Central Chincha Island in 1913; and that they ate 1000 tons of fish a day.[1]

Rock Phosphate—In a rainy climate the phosphoric acid is leached out of the bird droppings, and carried into the underlying material which it converts into phosphate. Many of the bird-frequented islands are coral reefs, and

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[1] Cf. R. C. Murphy, *Bird Islands of Peru*, 1925 H. O. Forbes, *Ibis.*, 1913 (10), i, pp. 709-12.

consist of carbonate of lime, which is altered to phosphate of lime. The phosphate may at first form a thin impermeable crust which may be broken by the collapse of solution cavities in the underlying limestones, and the pieces are cemented into phosphate breccia. In volcanic islands the phosphoric acid produces phosphate of alumina, such as the phosphatized trachyte of Clipperton Island in the Pacific Ocean off Mexico. Phosphate of alumina is more expensive to convert into superphosphate, and less valuable as a fertilizer than phosphate of lime; it is used for some special purposes, such as the treatment of sewage.

The phosphate of Christmas Island south of Java includes phosphatized volcanic rocks and coral reefs, and phosphatic breccia; and these rocks are traversed by thin veins of staffelite, a fibrous and concretionary variety of fluo-apatite, which show that the phosphoric acid was introduced in solution, doubtless as Andrews suggested from once overlying guano[1]

Nauru was discovered in 1798 and named Pleasant Island. A block of rock from it, regarded as fossil wood, was used in Sydney as a door weight. The recognition of its nature led to the discovery that Nauru and Ocean Islands contain about 100 million tons of high-grade phosphate. Cargoes are shipped averaging 85 to 88 per cent. of tricalcic phosphate ($Ca_3P_2O_8$). The phosphate occurs in depressions between pinnacles of limestone, and it does not pay to work deeper than 20-30 feet. H. B. Pope (*Austral. Indust. and Min. Stand.*, 15 February, 1923) regards the phosphate as derived from bird guano, though few birds live on the islands at present (cf. L. Owen, *Q.J.G.S.*, lxxix, 1923, pp. 1-14).

Lagoon Phosphate—Some important beds of phosphate of lime are formed in tropical and subtropical lagoons. Dead animals are washed into them and their bones and fish remains collect in patches, whence the current sweeps away the finer sediment. The bones may be dissolved and redeposited in nodules of earthy phosphate of lime, which are then known as coprolites.

The term coprolite was given to the fossil dung of reptiles

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[1] C. W. Andrews, *Monogr. Christmas Island*, 1900, pp. 290-1. The staffelite veins are described by the author, *Tr. G. Soc. Glasg.*, xvi, 1917, p. 134, pl. VI.

and fish. True coprolites are usually cylindrical or ovoid in form, and have a spiral mark impressed by the wall of the intestine. The bulk, however, of the coprolites used by the phosphate industry are concretionary nodules which may derive their phosphoric acid from either bones or dung. Such lagoon and nodular deposits are represented by the coprolite beds of the East of England, and among the phosphates of Florida, and South Carolina, on the coast of the Unites States. Some of the American coastal phosphates may have been formed by the alteration of limestone reefs or islands from deposits of guano.

Some lagoons were underlain by limestone which has been phosphatized by acid from above. This phosphate usually occurs in isolated masses and hummocks, owing to the irregularity with which the phosphoric solutions percolated through the overlying deposits or penetrated the limestone. The American coastal phosphates in 1925 yielded 3,000,000 tons.

GRANULAR PHOSPHATES AND PHOSPHATIC CHALK—Granular phosphatic limestones and phosphatic chalk represent another important source of phosphate. The phosphoric acid in sea-water may act upon the microscopic shells of dead organisms and convert them into phosphate of lime either in their fall through the sea-water or while lying on the sea-floor. In most marine deposits the proportion of phosphatized shells is small, but on shoals and parts of the sea-bed swept by strong currents, the calcareous organisms may be broken up and removed, while the harder and less soluble phosphatic shells remain as layers of granular phosphate. Layers of phosphatic chalk occur in the English chalk as at Taplow; in the North of France and Belgium this process has produced larger beds which supported the phosphate industries of those countries. Some of the more massive occurrences, as in the Somme valley, have been attributed to mineral springs. In warmer seas the process has formed thick beds of limestone charged with granular phosphate in Algeria, Tunis, and parts of Egypt. The Carboniferous Limestone of the Rocky Mountains belong to this group, and include large reserves of granular phosphates which are too remote from fields where fertilizers are required to be worked profitably at present.

The United States had for long the largest output of phosphate, with over 3½ million tons in 1925; it has been surpassed by North Africa which in the same year yielded over 4,200,000 tons; the South Pacific Islands were third with 450,000 tons.

Phosphatic fertilizers are of such value especially for cereals that anxiety has frequently been expressed as to the permanence of the supply. When President Rooseveldt aroused the United States to interest in the conservation of mineral resources, it was estimated that the available phosphates would only last twenty-five years. It was urged that export should be stopped so that America might not be drained of its indispensable phosphates for the benefit of the worn-out soils of Europe. Later investigations have shown that even if the output were trebled, America has enough high-grade phosphate to last for 1100 years, and Northern Africa has over 300,000,000 tons; so there is no fear of a phosphate famine. The present generation is no more to be blamed for using what it needs than were the Phœnicians for working the alluvial tin of Cornwall regardless of the future needs of the tinned meat trade. As minerals are irreplaceable, they should be used economically but also regardful of the commercial maxim, "If you have an asset, use it while you can." The collapse of phosphate mining in England was due to the discovery of richer and more cheaply worked foreign deposits with which the English mines could not compete. If legislation had restricted the output of British phosphate to make the supply last longer, much of it would have been left unused, and Britain would have lost an addition to her capital and the profit derived from the manufacture of foreign phosphate.

CHAPTER XVIII

THE SALT DEPOSITS[1]

Composition of Sea-Water—The characteristic feature of sea-water is its saltness. The analyses by Dittmar of the many samples of sea-water collected by H.M.S. "Challenger" (1873-6) show the following composition:—

	Per cent.
Sodium chloride	77·758
Magnesium chloride	10·878
Magnesium sulphate	4·737
Calcium sulphate	3·600
Potassium sulphate	2·465
Calcium carbonate	0·345
Magnesium bromide	0·217
	100·000

The variations from this composition are slight except near the mouths of great rivers and in enclosed seas, i.e. a sea with only one outlet, such as the Mediterranean and the Baltic. If an arm of the sea be cut off from the ocean and its water evaporated, the salts are deposited in the order of their insolubility. When 37 per cent. of the water has been removed the calcium sulphate is deposited; when 93 per cent. has gone common salt (sodium chloride) and sodium sulphate are precipitated; the magnesium chloride, potassium chloride, and bromine are left in the brine which, from its taste, is known as bittern. The chlorides in the bittern are so soluble that they are not deposited unless all the water

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[1] "The Geology of Potash," with some account of the German salt fields has been given by the author, *Tr. G.S. Glasgow*, xvi, 1916, pp 12-33, pl. I.

be evaporated. As sea-water contains on an average 35 parts of salt per 1000, the evaporation of 1000 feet of sea-water would deposit a layer which, if compact, would be about 15 feet thick. If the basin were again covered by the sea the magnesium and potassium chlorides of the upper layer would be dissolved; another 15 feet of salt per 1000 feet of evaporated water might be laid down, and this process of submergence and evaporation might go on indefinitely. The evaporation of 30,000 feet of sea-water, the approximate maximum depth of the oceans, would deposit only 450 feet of salts. Yet some salt deposits are thousands of feet in thickness.

CONCENTRATION IN SALT LAKES—The deposits in an inland sea (i.e. a sea completely cut off from the oceans) that receives river-water containing bicarbonate of lime, would contain precipitates of carbonate and sulphate of lime; by this precipitation the sea-water would gradually lose its carbonates and sulphates. Further evaporation would precipitate the sodium chloride and the water would be left as a bittern containing magnesium and potassium chlorides, which might be deposited as carnallite ($MgCl_2$, KCl, H_2O). Such conditions may be illustrated by the Dead Sea. The quality of the water poured into it from the Jordan is shown by the analysis A; the composition of the Dead Sea water is shown (B) from a sample from the depth of about 600 feet, 5 miles from the northern end:—

	A.	B.
Cl . . .	41·4	67·84
Br . . .	—	1·75
SO_4 . . .	7·22	·22
CO_3 . . .	13·11	tr.
Na . . .	18·11	10·0
K . . .	1·14	1·79
Ca . . .	10·67	1·68
Mg . . .	4·88	16·7
SiO_2 . . .	1·95	tr.
Salinity . .	·08 per cent.	24 per cent.

All the carbonate and most of the sulphate of lime introduced from the Jordan is precipitated, and the Dead Sea water retains the potassium, magnesium chloride, and bromine. The ratio of magnesium to sodium is raised from 1 to 4 in the Jordan to 8 to 5 in the Dead Sea. The rate of this change can be inferred from the amount and composition of the Jordan water, and the age of the Dead Sea has been thereby calculated as 50,000 years.

THE GERMAN SALT FIELDS—Some deposits of salt and gypsum have been formed by the simple evaporation of sea-water which has been cut off in lagoons; such are the layers of gypsum found on coral islands, and the lenticular patches of salt in the Permian red rocks of Kansas and the salt beds of Cheshire. The most important salt field is that of Central Germany, and its story, as illustrated by Fig. 54 may be summarized as follows. An ancient land, composed of

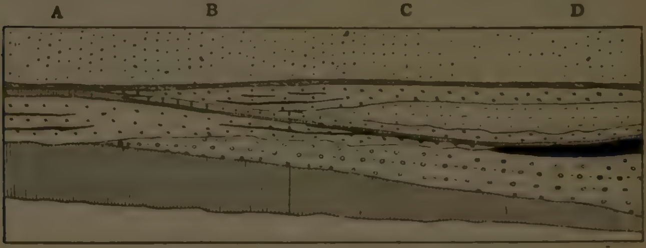

FIG. 54.—GERMAN SALT FIELDS.

Diagrammatic section across the German salt fields, showing the general sequence and relations of the deposits. (Simplified from a section by Everding.)

A = Werra type.
B = Hanover type.
C = S. Harz type.
D = Stassfurt type.

□ Pre-Carboniferous and culm.
▥ Upper Carboniferous Rothliegende, lower Permian.
⁘ Older primary rock-salt.
⁘ Secondary rock-salt.
⁘ Younger primary rock-salt.
☰ Potash salts with their cover of clay.
⁘ Main bed of anhydrite.
■ Upper Zechstein, upper Permian.
⁘ Bunter sandstones, lower Trias.

pre-Cambrian to Lower Carboniferous rocks, sank beneath the sea and was covered by beds laid down in the Upper Carboniferous and Permian Sea. The earlier beds were ordinary marine deposits, which were followed by red shales and a dolomitic limestone (the Zechstein); their stunted fossils show that the connection between the sea of Central Germany and the outer ocean had been closed, so that the water had changed in composition, and the less adaptable animals and plants had perished. As the water evaporated salts were precipitated; the series began at Stassfurt, in the centre of the basin, with a thick deposit of rock-salt interbedded with layers of anhydrite ($CaSO_4$). These minerals occur in such regular alternation as to suggest precipitation by the annual change from winter to summer. The lower series of rock-salt and gypsum was succeeded by a bed containing potash and magnesium salts, so that the sea-water and the bittern were both evaporated. These very soluble salts were then covered with a layer of clay; the sea again submerged the area; a fresh layer of limestone was deposited, and was followed by a thick bed of anhydrite and a younger series of interbedded rock-salt and anhydrite. Above this series occurs a widespread sheet of massive rock-salt due to the redeposition of salt dissolved out of the underlying beds. Then followed another invasion of the sea, which deposited another layer of Zechstein and prevented the deposition of a second layer of potash salts. This upper limestone was covered by the red sandstones of the Bunter or Lower Trias, which were deposited under desert conditions on land.

In other parts of the German salt basin the sequence of events was different. Thus towards the valley of the Werra River (Fig. 54 A) the primary rock-salt was not deposited, but a secondary rock-salt was formed, doubtless of material dissolved from the older beds, and the evaporation of occasional brine pools deposited patches of potash salts. Then followed two further layers of Zechstein and a widespread thick sheet of Bunter sandstone. The South Harz (C) and the Hanover district (B) show an intermediate condition, with the lower secondary rock-salt of the Werra basin intercalated between two great primary salt deposits as at Stassfurt (D).

Intrusive Salt Deposits and Salt Domes—Some salt deposits are of such enormous thickness that the simple evaporation of an inland sea does not explain them. Thus a bore near Berlin at Speerinburg—which is historic from its evidence as to the increase of underground temperature—passed through 3000 feet of rock-salt without reaching the bottom. To produce such a quantity would require the evaporation of seven times as much sea-water as covers the deepest part of the existing oceans. Moreover, some salt deposits, instead of occurring in horizontal sheets regularly interstratified with sediments, are intruded in tongues which have disturbed the adjacent beds and produced slipped and slicken-sided surfaces. These tongues gave rise to the theory that salt is sometimes of igneous origin, a view supported by the abundant chlorine vapours emitted through volcanic vents. Dr. G. E. Pilgrim (*Mem. G.S. Ind.*, xxxiv, 1909, p. 68) explains the salt at Kamarij near the Persian Gulf as due to the injection of a volcanic magma of sodium chloride.

The aqueous theory has the recommendation that though salt deposits occur at many different periods in the earth's history their constant association with red beds or limestones of an abnormal character indicates their deposition in lagoons. They thus occur in the Cambrian in the salt range of India and in Persia; in the Devonian of Russia and the United States; in the red beds of the Permian and Triassic Systems in England, Germany, and the United States; and in Kainozoic beds in Eastern Europe, Persia, and Somaliland. The abnormal thickness of salt deposits can be explained by aqueous deposition by the "bar theory" of Ochsenius, which may be illustrated from the Caspian Sea. That sea has no connection with the ocean and receives at its northern end the waters of the Volga and Ural Rivers. The southern end is bordered by dry steppes and the evaporation during the dry season is high. Karabugas, an extensive basin on the eastern shore, is connected with the Caspian by shallow channels, through which the inflow to replace the water lost by evaporation introduces 3500 tons of salt a day. The change produced in the Caspian water is illustrated by two analyses quoted from A. C. Clarke (*Data of Geochemistry*, 1924, p. 169):—

	A.	B.
Cl	41·78	50·26
Br	·05	·08
SO_4	23·78	15·57
CO_3	·93	·13
Na	24·49	25·51
K	·60	·81
Ca	2·60	·57
Mg	5·77	7·07
Salinity	1·267 per cent.	16·396 per cent.

They show that the northern Caspian (A) receives much normal river-water, and that the water in Karabugas (B), has lost most of its carbonate, and nearly all its sulphate of lime, and is almost a bittern. During the dry season sulphates of lime and sodium are deposited on the floor of Karabugas, but none of the chlorides; for they escape as an outflow of heavy brine. If the bar between the Caspian and Karabugas were raised so that the basin were isolated, then further evaporation of the water would precipitate the sodium chloride as rock-salt and the chlorides of potash and magnesium as carnallite. If the wind covered the basin with clay, these deposits might be preserved. The load of salts might cause the subsidence of the area, and enable the sea to reflood the basin. Another sheet of gypsum and salt would be deposited. Many successive subsidences would result in a great thickness of salt deposits.

Thick beds of salt would also be produced if an extensive inland sea were reduced by evaporation and its water concentrated in one depression and the salts all deposited there. If the salt deposits were 15 feet thick for each 1000 feet of sea-water, and they were laid down over only 1 square mile for every 100 square miles of the dwindling sea, the deposits over the mile would be 1500 feet in thickness.

Neither the bar theory nor that of concentration in one part of a basin is exactly applicable to the German salt deposits, for sea-water does not contain enough calcium to produce the enormous quantities of sulphate of lime that occur there. The basin while undergoing evaporation, must have continually received river-water containing lime. Accordingly the bar theory was rejected for Central Germany by Erdmann, who thinks that the deposits were laid down in a depression that held the last waters of an isolated Permian Sea which continually received river-water. It has also been rejected by Walther, who holds that the salts were not deposited directly from sea-water, but were leached from older marine deposits and concentrated on the beds of salt lakes.

One section of the German salt fields covers 24,000 square miles, and is estimated to contain 3½ million million tons of potash salt and vastly larger supplies of rock-salt. A sea large enough to have supplied so much salt should have maintained a moist atmosphere and prevented continuous and complete evaporation. The bar theory, suitably adapted appears best to fit the facts; for it explains how water from the outer ocean could be continually poured into a basin undergoing evaporation and receiving large supplies of lime from rivers.

Evaporation of sea-water does not explain intrusive salt masses and the salt domes around the Gulf of Mexico. The first well-established salt dome was found at Rang-el-Melah in Algeria, 14 miles N.W. of Jelfa. It was described by Ville (*Ann. Mines* (5), xv, 1859, pp. 366-73, pl. III) and is a circular mass bounded on one side by Lower Cretaceous rocks and on the other by middle Kainozoic. The beds dip away from it, and are in places inverted. They include breccia with thin veins of copper and iron pyrites. Some adjacent salt beds are ordinary marine deposits; but Ville concluded that this mass was intruded as a saline clayey magma, which forced its way through the Cretaceous and Kainozoic beds.

The Jennings oilfield near New Orleans beside the Gulf of Mexico was discovered as some shallow salt lakes had persistent films of oil and escapes of gas. Bores sunk beside these salt lakes in search for the source of the oil led to the startling discovery below them of vertical pillars of salt. A bore into Anse la Butte, about 100 miles W.N.W. of New Orleans, passed through 2263 feet of almost pure salt, then through 70 feet of sediments, and ended in an unknown thickness of salt. Adjacent bores proved that the salt is a cylindrical mass 1000 feet in diameter, with the sides so steep that a bore 300 feet away from it passed through up-tilted sand and clay, and met with no salt. Horizontal tongues of salt sometimes pass from the dome into the adjacent beds. More than sixty of these salt domes have been found during the development of the Louisiana oilfield, some by the use of the torsion balance and the earthwaves due to explosions. The salt dome at Spindletop gave the clue to the oilfields of Mexico.

Salt domes have been explained by igneous action; but they are secondary formations due to ascending water. The salt dome area is underlain by Kainozoic and Cretaceous rocks, and doubtless by salt-bearing beds belonging to the Trias or Permian. Most of the Louisiana salt domes are regularly arranged, as at the angles of a network; they probably occur where intersecting faults afforded a channel up which water charged with salt escaped from the underlying red sandstones. As the water approached the surface it was cooled and deposited its salt in the channel. Further salt was added to the base of the block and the crystallization of this salt pushed the mass like a spear-head through the soft wet clays (cf. Fig. 63 *j*).

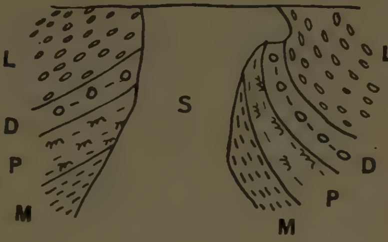

FIG. 55.—SALT DOME AT THE BAICOI OILFIELD, RUMANIA.

L, sands and gravels with land and fresh-water shells; D, Dacic—oil beds with lignite. P, Pontic—marine marls; M, Meotic — Pliocene fresh-water sands. S, salt intrusion. (After Slomnicki and Meyer, 1925.)

The Egeln dome in Germany (Fig. 56) contains a vertical thickness of 4000 feet of continuous salt. This thickness is due in part to the salt being uptilted and repeated by overthrust faults; but the salt has been partly squeezed into this pillar and enlarged by solution and redeposition during the faulting. The faults are of Kainozoic age and were due to disturbances connected with the uplifting of the Alps. A salt dome at Aschersleben occurs beside the great faults along the compressed fold of the northern Harz Mountains. A similar salt intrusion occurs at Baicoi in the Rumanian oilfields (Fig. 55).

In the Salz-Kammergut in Eastern Austria tongues of salt project into clays like igneous intrusions, and the clays around have been disturbed and moved by the entrance of the salt. The salt was apparently deposited in the area by evaporation, and during subsequent earth-movements some of it was dissolved and redeposited in tongues, which as they grew forced their way into the shales.

POTASH SALTS

VALUE IN AGRICULTURE—Potash is indispensable in agriculture as a fertilizer, owing to the amount which is removed from the soil in each crop. A wheat crop of 30 bushels to the acre removes 28 lb. of potash, a hay crop of 1½ tons to the acre 56 lb., a 6-ton crop of turnips 78 lb., and a 22-ton crop of mangels 300 lb. The potash in soils is mainly derived from the felspars and felspathoids. The potash in these minerals occurs as a silicate; during weathering it is dissolved as bicarbonate and carried by rivers to the sea. In the Thames at Kew 1½ per cent. of the dissolved matter in the water is potassium, and there is 1 lb. of potassium in every 90 tons of water. Waters which flow directly from areas of felspathic rock contain larger amounts. Potassium amounts to 6·71 per cent. of the salt in the Eger, a tributary to the Elbe in Saxony, and to 4 per cent. in Lac de Champex in the Valais in Switzerland.

DERIVED FROM SEA-WATER—Potassium occurs in the sea as sulphate and chloride; some of it is deposited as glauconite, which colours greensand; some potash is extracted by seaweeds, of which the burnt ash or "kelp," was formerly the chief source of supply.

Potassium chloride, owing to its extreme solubility, remains in evaporating sea-water until the water has been almost completely removed. Potash chloride collects in such lakes as the Dead Sea. When such waters are completely evaporated their potash is deposited as one of a series of sulphates or chlorides. The first potash is precipitated as a sulphate, such as glaserite (K_2SO_4), which may be associated with the other simple sulphates, kieserite ($MgSO_4$, H_2O), glauber salt (Na_2SO_4), and anhydrite ($CaSO_4$), and also with such double sulphates as glauberite (sulphate of calcium and

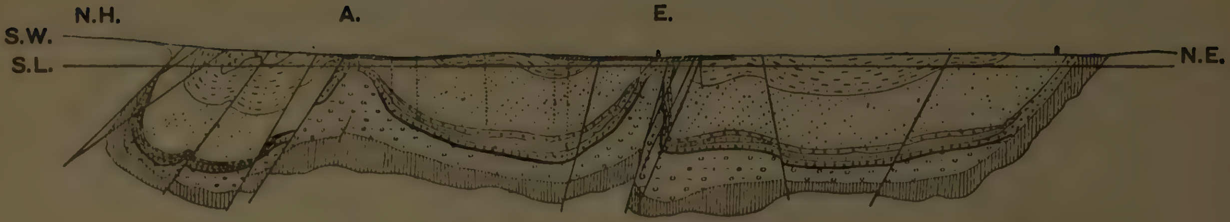

FIG. 56.—GERMAN POTASH FIELDS.

Diagrammatic section across the German potash fields (after Everding), from the northern edge of the Harz Mountains (N.H.) across the salt dome of Aschersleben (A), and the faulted dome of Stassfurt-Egeln (E).

- ▨ Kainozoic.
- ⁘ Cretaceous.
- ▭ Keuper—upper Trias. Muschelkalk—middle Trias.
- ⁘ Bunter sandstones—lower Trias. Upper *Zechstein*—upper Permian.
- ⁘ Main bed of anhydrite.
- ▤ Potash salts with their cover of clay.
- ⁘ Younger primary rock-salt.
- ⁘ Secondary rock-salt.
- ⁘ Older primary rock-salt.
- ▥ Low mid. *Zechstein*—upper Permian, Rothliegende—lower Permian, and upper Carboniferous.
- ▭ Pre-Carboniferous and culm.

sodium), langbeinite (double sulphate of magnesium and potassium); and with the triple sulphate polyhalite (sulphate of calcium, magnesium, and potassium with two molecules of water). After the sulphates follows the precipitation of the chlorides, such as sylvite (KCl) which may be combined with magnesium chloride, as carnallite ($KCl, MgCl_2, 6H_2O$), or as hartsalz, a mixture of sylvite, rock-salt, and kieserite. Intermediate between the sulphates and the chlorides is kainite—sulphate of magnesia combined with chloride of potassium and water ($MgSO_4, KCl, 3H_2O$). These minerals may be formed by the complete evaporation of an inland sea, of which the waters have remained nearly saturated for a long time.

Secondary Concentrations—Potash salts, owing to their extreme solubility, are less abundant than rock-salt; for the potash is less often deposited, and more likely to be removed in solution. The largest supply of known potash salts is in Central Germany, where, as explained on page 209, the bittern was occasionally evaporated and beds of primary potash laid down. Even there, however, owing to the solubility of the potash salts many of the beds of commercial importance are secondary, and have been redeposited. The upturned edges of a series of beds of rock-salt, carnallitite (i.e. impure carnallite), and kieserite is covered by a sheet of kainite which occasionally projects into the underlying beds. This kainite is of secondary origin for it is traversed by the upward continuation of layers of rock-salt which have resisted solution; whereas the carnallite and kieserite, owing to their greater solubility, have been replaced by kainite. At the Hercynia Mine near Vienenburg, rock-salt, hauptsalz (a mixture of carnallite, rock-salt, and kieserite), anhydrite, carnallitite, and sylvinite (i.e. $KCl + NaCl$), are capped by secondary deposits of sylvinite and kainite, which have not also replaced the rock-salt or anhydrite. The secondary origin of the sylvinite is further proved at the Ronenberg Mine, as a fault has displaced the rock-salt and anhydrite, but not the sylvinite, which occurs along and across the fault plane.

These secondary potash deposits like the German salt domes were due to the percolation of water along fractures contemporary with the uplift of the Alps.

Diligent search has been made for other supplies of potash and many efforts to extract it from leucite rocks and potash-felspar, as well as from seaweed and sunflowers.

Beds of potash salts have been found where large sheets of sea-water have been evaporated. The basin of Afar at the southern end of the Red Sea is geographically well suited for the formation of salt deposits; for it is below sea-level and could have been repeatedly flooded from the sea. Potash deposits there have been worked to some extent.

The two most important non-German sources of potash are some beds left by the evaporation of an Oligocene lake near Mulhouse in Alsace. The deposits were developed under the control of the German Kali Syndicate, but after the War were for a time worked independently. A second field is in the north-east of Spain near Cardona and Suria; the potash minerals include carnallite, kainite, kieserite, sylvinite, and polyhalite, and rest on a thick block of salt and gypsum.

Some potash has been extracted from the mud of lakes, such as Searles Lake in California, which receive the drainage from rocks rich in potash.

At one time objection was taken in Germany to the export of potash on the ground that it would all be wanted by the local farmers. Ochsenius was instructed to report on the available supplies; his report that one of the German fields could maintain an output of 5,000,000 tons per annum for over 600,000 years showed this fear was futile. The output is however limited to safeguard the water supply; as otherwise the waste waters would render the rivers too salt for drinking and would be fatal to the fish.

PART IV

ENGINEERING GEOLOGY

CHAPTER XIX

WATER SUPPLY

Fresh water is one of the most essential of human needs. The people on some South Sea Islands have no means of catching rain, the wells are brackish, coco-nut milk is the usual drink, and, according to Admiral Wharton, they enjoy the luxury of fresh water only when it can be skimmed off the lagoons after heavy rain. As a rule fresh water is a primary need, and as people become more fastidious as to its quality and extravagant as to quantity, competition is keen for the unappropriated supplies.

The Three Sources of Water—Meteoric—Most fresh water is provided by rain and is therefore said to be meteoric. Rain is mainly due to evaporation from the sea. The moisture in the air is condensed and either falls as rain or is deposited on cool surfaces as dew. The pre-historic dew-ponds of the South of England were attributed to dew—" Only the dew-pond on the height, unfed, which never fails "—but they are fed by rain-water which is protected from percolation and evaporation by the structure of the pond (E. A. Martin, *Dew-ponds*, 1915). The average annual rainfall of the British Isles is estimated by Dr. H. R. Mill at about 40 inches; and as 1 inch of rain provides 22,622 gallons per acre, 40 inches on an acre amounts to 900,000 gallons. The area of the British Isles being 77,683,084 acres, and the population about 44 million, the rain supplies each inhabitant with 1½ million gallons a year, or 4000 gallons a day.

Rain, as a product of distillation, might be expected to be chemically pure; but it washes from the air dust, dirt, smoke, acids, and bacteria. Snow collected off the roof of the *Lancet* Office in London contained :—

Soot, coal dust, and tar . .	30·32 grs. per gall.
Mineral matter in solution .	4·20 ,, ,,
Organic matter in solution .	7·84 ,, ,,
Free ammonia . . .	·07 ,, ,,
Organic ammonia . . .	·01 ,, ,,
Sodium chloride . . .	1·33 ,, ,,
Sulphuric acid . . .	3·36 ,, ,,
Nitric acid	Traces.

The rain near the sea contains sea-salt derived from evaporated spray, and some is carried far inland. This salt is harmless in moderate quantities, but introduces uncertainty in the use of chlorine as a test of organic pollution.

CONNATE—Some water is enclosed in sedimentary rocks during their deposition and is stored in them as "connate water."

PLUTONIC OR JUVENILE WATER—There was for long widespread reluctance to admit the existence of any water on land other than that derived from the rain. Deep wells, hot springs, and volcanoes were regarded as all discharging meteoric water which had percolated underground and been forced to the surface, either by the internal heat of the earth, or by the pressure of water at higher levels in the water-bearing bed. Thus at the Conferences on "Water Supply and Distribution" in 1884, G. J. Symons, the meteorologist, declared that "all water supply comes from the clouds," and James Mansergh, representing the engineers, said "all supplies of water, whether found upon the surface or below it, in underground depths, are derived from the rain which falls upon the earth." C. S. Slichter (*U.S.G.S.*, *Wat. Sup. Pap.*, 67, 1902) adopts the same view.

Geologists have long held that the rainfall is supplemented by water from the interior of the earth, which is described as plutonic, or magmatic, or "juvenile" (cf. p. 22).

Nearly all primary rocks contain water, which is seen under the microscope in the fluid cavities of quartz in granite. This water usually amounts to between 1 to 5 per cent. in igneous rocks ; and owing to their bulk a small percentage amounts to a prodigious quantity. This water tends to escape and is discharged by hot springs and volcanic eruptions, which give forth vast clouds of steam that falls as torrential rain. According to Fouquet, Etna in 1865 discharged in about three months sufficient water to fill a reservoir a square mile in area and 26 feet deep. The view that such water is all derived from rain was supported by the claim of Ehrenberg that lavas contain the shells of diatoms, and by such reports as that Cotapaxi erupted fish; but the diatoms which Ehrenberg found in lava probably reached it during the dusting of his laboratory, and the arguments from subterranean fish are equally invalid. Much volcanic steam is probably of plutonic origin and is added to the surface water.

Mining experience shows that water is constantly arising from the interior; thus below the zone containing meteoric water there is often a thick dry belt, in which are found, as at Bendigo, the Comstock Lode, and the St. Gothard Tunnel, springs of hot deep-seated alkaline water. The chemical composition of the water from many hot springs shows that it cannot be derived from the local rocks. The objections to the existence of plutonic water were abandoned after the experience at the Simplon Tunnel. Many workmen were scalded to death by irruptions of water far hotter than was expected from the depth. Some of this water was free from sodium chloride, which is universally present in meteoric water. Sir F. Fox (*Proc. Inst. Civ. Eng.*, clxviii, 1907, p. 77) remarked of one spring, which discharged 3036 gallons per minute of water at 114·6° F. and contained 106 grains per gallon of mineral matter, that "the complete absence of chlorine is believed to be unique, and seems to indicate that the water was possibly entirely plutonic, having never been on the surface of the globe." There is no single absolute chemical test to distinguish between meteoric and plutonic waters; water is probably plutonic if it has no or but little chlorine, or contains boric acid where there are no local borates from former volcanic eruptions, or its constituents are not those that would be derived from the adjacent rocks.

The deep-seated origin of the hot springs of Carlsbad in Bohemia was suggested by Gœthe and proved by Suess. These springs have been flowing for at least seven centuries, for the Emperor Carl IV was cured at them of wounds received from English archers at the battle of Crecy (1346).

The springs are in granite, which would not provide their sodium sulphate, sodium carbonate, and sodium chloride, while the waters have also traces of lithium, arsenic, antimony, tin, and rubidium. The water brings up 2,000,000 lb. of sodium sulphate and carbonate a year, while the deposit of carbonate of lime chokes the channels, and causes explosions unless the outlets are re-bored. The springs vary in temperature from 164° F. at Sprudelkessel, said to be the hottest spring in Europe, to 118° at Schloss Brunnen; all the springs yield the same constituents and in the same proportions. The water obviously comes from a deep-seated source below the granite.

The quantity of plutonic water is incalculable; but the amount discharged by volcanic eruptions and hot springs is enormous, and as geological time is estimated in thousands of millions of years the contributions must represent an important addition to the surface waters. The Carlsbad springs discharge 2,000,000 gallons a day, which in 1500 million years, would have raised sea-level about 160 feet. The life of any single hot spring is probably short geologically; but as one channel is closed another is opened elsewhere. The oceans must have been much increased by the unceasing discharge of plutonic water. Part of the flow from hot springs is meteoric water. The water of the hot springs and geysers of the Yellowstone Park in the Rocky Mountains has been claimed as surface water that has been expelled after working its way 8000 feet deep. Half the discharge from the springs of Iceland and California has also been considered to be meteoric. The efforts to explain the heat of these waters by chemical and radioactive processes are generally dismissed as unsuccessful. An American symposium on hot springs (*Journ. Geol.*, xxxii, 1924) concluded that the heat must be plutonic although part of the water may be meteoric. As the heat is plutonic probably much of the water is so also (cf. A. L. Day and E. S. Shepherd, *Bull. G. Soc. Amer.*, xxiv, 1913, p. 606).

Disposal of Rainfall—Rain-water is removed from the land in three ways—run-off to the sea, return to the air by evaporation, and percolation underground.

" Run-off "—The " run-off " is determined by measuring the discharge of all the rivers. The percentage varies from practically 100 per cent. on a small rocky islet, to nothing in some desert regions. The amount varies with climate, vegetation, the geological and geographical character of the country, and the nature of the rainfall. The average rainfall in the Thames valley for forty years was 28½ inches, and during that period the run-off disposed of 8 inches of rainfall p.a., or 28⅛ per cent. For the earth as a whole the run-off is estimated at about one-fifth of the rainfall.

Evaporation—Evaporation is measured by evaporation gauges, of which the most reliable are tanks usually a square yard in area, floating in large sheets of water, as at Croton Reservoir near Boston and the Lea Valley reservoirs in London. The annual evaporation around London, as at Hemel Hempstead, is 21-24 inches, out of 28·18 inches of rain, or over 75 per cent. In Britain the average evaporation from lakes and reservoirs is estimated at about 20 inches a year; in Egypt (B. F. E. Keeling, *Nature*, lxxxi, 1909, p. 403) ⅙ inch a day; in India 60 inches a year; in Central Australia over 100 inches a year; in many areas evaporation removes the whole of the rainfall. The rate varies less from year to year than might be expected; for in a wet year, though evaporation is less from an equal surface of water, the evaporating surfaces are wider and counterbalance the slower rate. In still weather the evaporation from a large body of water is nearly the same for each hour of day and night; on a dry day in winter the evaporation may be greater than on a still day in summer.

Percolation—The water that percolates underground is protected from organic pollution and from loss by evaporation, and as it may flow to arid districts it is often of high importance. The proportion of rainfall available for percolation is however often small, and may be nothing. The amount is measured by percolation or Dalton Gauges. They consist of a block of undisturbed ground, usually a square yard in area, around which are placed watertight walls and floor. The water that percolates to the bottom drains to a measuring vessel. The amount of percolation to different depths is determined by adjacent gauges of the depths required.

Much water percolates underground from rivers, by seepage through the sands on the bed; the loss depends on the speed of the river. A 90-feet channel at Mildura, on the Murray River, which lost 32¼ inches of water a day when the stream was flowing, when the water was stagnant lost ¼ inch in the first hour, and after the first day lost only 1 inch per day. Stagnant water deposits clay on its bed and renders the channel watertight; a flowing stream keeps the clay in suspension and its bed porous.

The water that percolates underground forms a widespread sheet in the pores, crevices, and joints in the rocks; the upper surface of this sheet is known as the "water-table" (Fig. 57). A pit sunk below the water-table is filled with water and serves as a well; where the ground falls below the water-table in a valley or hill-side, the water outflows as a spring. The water-table is an undulating surface, which repeats the relief of the ground above though the variations are gentler; it is at the surface on the shore of a lake or the sea; it rises below hills and falls below valleys. Its varying height depends on surface-tension, by which water adheres to a surface in a thin film, so that it spreads over particles of earth and keeps them wet. Surface-tension and friction prevent the water-table becoming horizontal. As surface-tension is lessened by heat, a rise of temperature sets water free, and thus springs and drains in soils may have an increased flow after warm weather.

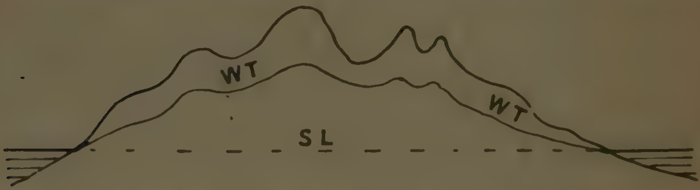

FIG. 57.—POSITION OF THE WATER-TABLE.

The position of the water-table, WT, in an irregular island. SL = sea level.

THE CIRCULATION OF SUBTERRANEAN WATER—PIEZOMETERS—The passage of water through rocks is subject to the laws that regulate its flow through tubes. Tubes which are less than $\frac{1}{50}$th of an inch in diameter and spaces less than $\frac{1}{100}$th of an inch wide are said to be capillary (or hair-like) and water creeps along them by "capillary attraction"; it may thus rise against gravity, but it cannot be forced through by pressure of a "head" of water. Larger tubes and spaces are super-capillary, and water is driven through them by gravity and gas-pressure. In small tubes, which may be compared to the small fissures and passages in rocks, the flow of water is controlled by friction, which increases directly with a decrease in diameter and with an increase in length, increases as the square of the velocity, and increases with the roughness of the inner surface of the tube.

In tropical and warm temperate countries with an annual rainfall of less than 20 or 25 inches, and a fine-grained uniform soil, run-off and evaporation may remove the whole of the rainfall, and there be none left for percolation. Nevertheless the upper layers of the crust have been often represented as so charged with water that a deep well will be successful anywhere. A. Delesse (*Bull. Soc. Géol. Fr.* (2), xix, 1861, p. 64) estimated the amount of subterranean water as about equal to that in the oceans, and Slichter (*U.S.G.S.*, *Water Sup. Pap.*, No. 67, 1902, pp. 14-15) accepted a third of this quantity. The existence of this subterranean sea was based on the principle that a current of water uses the whole channel open to it. Thus when a stream of water enters a trough at one point and flows out at the opposite point, it does not pass straight across the trough; the current widens and deepens till all the water shares in the movement. Hence it was held that water percolating through the crust must spread widely downward and sideways until it saturates the crust. Deep bore holes and mines, however, after passing through a wet zone often reach rocks that are quite dry, although they were deposited in the sea and must have been saturated with connate water.

The slope of the water-table depends on the friction. Water poured into an empty U-tube rises to the same level in both arms, because the friction is negligible. If the tube be filled with sand, the friction is appreciable, and water poured into one arm rises slowly in the other; if the lower part of the tube be filled with clay the water only penetrates the clay by surface-tension, and the "head" or pressure of the water has no effect, and none passes through the clay into the other arm.

The height to which water rises in rocks may be illustrated by a series of "piezometers" or pressure meters, as in Fig. 58. If a horizontal pipe from the lower part of a water tank is closed at the outer end by the tap T and bears a row of vertical tubes (P1, P2, P3, P4), the water will rise in each of them to its height in the tank, and that level is the hydrostatic surface (HsS). If the tap be opened the water in the vertical tubes falls to a surface sloping from the water-level in the tank to the outlet. As the water is flowing, the conditions are hydraulic, and the inclined surface, Hl Sl, is the hydraulic slope or gradient. This gradient depends on the velocity of the water along the pipe; the greater its velocity, the lower the water-level in the vertical pipes. The height of the water in each of them is the pressure-head; the difference of pressure-head between flowing and stagnant water is the "velocity-head"; the pressure-head and velocity-head together equal the hydrostatic-head. If the horizontal pipe be constricted (Fig. 58 B) so that the flow of water along it be reduced, or if part of it be filled with sand so that the friction is increased, then the pressure-head is raised. The hydraulic gradient therefore varies with the conditions in the outlet channel, and may be an irregular slope. If the pipes and the side of the tank were replaced by a block of porous sandstone the water would soak into the stone and flow through it to an outlet at the free end under

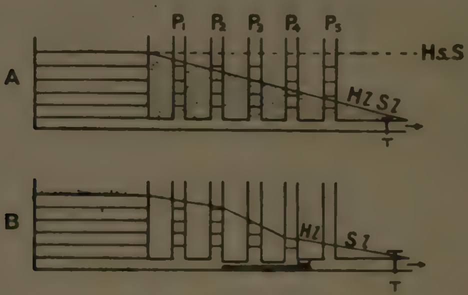

Fig. 58.—Water-Level.

Water-level in a series of piezometers P_1-P_5. HsS = Hydrostatic Surface, Hl Sl = Hydraulic Gradient.

conditions similar to that in the pipes. The block of sandstone would behave as a continuous chain of piezometers. If there were no outlet the water would saturate the block to the level of the water in the tank; the water-table would coincide with the hydrostatic surface. If there be a free outlet the water-table would be the hydraulic gradient from the water-level in the tank to the outlet, and would vary with the porosity of the sandstone. If the sandstone were replaced by a block composed of layers of sand and clay the water-table would be an irregular surface; the water would rise to different heights according to the permeability of the material; the greatest possible height would be that of the water-level in the tank. If part of the block were heated by a lamp, then the water near it might be raised above the hydrostatic surface by gas-pressure.

The resistance to the underground flow of water by friction limits the yield of wells. If a well be over-pumped a conical area around it is drained of water and the well fails until the "cone of exhaustion" is again filled from the surrounding bed. Wells on the seashore often yield fresh water, as they drain land water flowing to the sea; but if such a well be over-pumped sea-water enters the cone of exhaustion and the well becomes brackish.

The cone of exhaustion was used by George Stephenson in the construction of the Kilsby Tunnel near Northampton. It was feared that the tunnel could not be made until the whole of a water-logged bed had been pumped dry. Stephenson realized that by pumping a continuous series of cones of exhaustion the tunnel could be constructed although a sloping bank of water rose above it on both sides.

THE YIELD OF WELLS—WATER-STORAGE—The water-level in wells depends on the local hydraulic gradient. The yield of a well depends on the capacity of the adjacent beds or rocks as regards storage, permeability, and imbibition. The water-storage depends on the total amount of pores in a material, and varies with the uniformity of the grains. If a box be filled with shot of uniform size the total interspace between them is the same whether the shot be large or small. With a mixture of large and small shot, as the small shot occupy the spaces between the larger, the total interspace is reduced. Similarly in rocks; the amount of interspace is equal in a clay and in a conglomerate of uniform spherical pebbles; the interspace is larger in a clay than in a conglomerate with sand grains between the pebbles. In a clay the amount of pore-space available for water-storage is high; in a sandy conglomerate it may be low. The amount of space for water-storage depends also on the denseness of the rock. In newly-deposited mud the particles are loosely packed and the interstices are occupied by water; when the mud is compressed into clay or shale the particles are closer together; the bed may be reduced to a sixth of its original volume, and its water-storage is greatly reduced. The connate water is expelled as the material shrinks.

The *permeability* of a rock is its capacity for the entrance and passage of water. Clay is impermeable because its pore-spaces are so small that the water can only enter them by surface-tension. Sand is permeable because water readily flows through its wide spaces. Permeable rocks allow water both to enter and drain away quickly, and thus wells in them may yield large supplies.

The *imbibition* of a rock is its hold on the water in its pores. Chalk has a large water-storage, and readily absorbs water; but its particles are so minute that they have a large internal surface and hold water firmly. Hence though a bed of chalk may contain much water, unless a well in it reach a water-charged fissure the yield may be small; for owing to the high imbibition of chalk little of its water would flow into the well.

The three properties may be illustrated by the following comparison :—

	Water-storage.	Permeability.	Imbibition.	Per Cent. of Water available from Wells.
Sandstone . .	Often low	High	Low	High
Clay . . .	Large	Low	High	None
Chalk . . .	,,	High	,,	Low

The yield of water from rocks often depends on the joints and fissures. The water capacity of many compact igneous and metamorphic rocks is insignificant; but their joints may hold useful supplies, especially in the uppermost 10 or 20 feet (e.g. Wisconsin, *Geol. Surv. Bull.* 35, 1915, p. 350). The renewal of water in wells depends on the rate at which water percolates through rocks; and the movement is usually very slow. It may be a few yards a day through gently dipping sand, or 5 feet a day through a sandstone with a slight dip. The Dakota Sandstone in the west central part of the United States receives much water from rivers that rise in the Rocky Mountains, and it feeds wells far to the E. In part of the area the water flows through the sandstone from one to two miles a year (N. H. Darton, 1897, *18th Ann. Rep. U.S. Geol. Surv.*, pt. iv, p. 609; also *Prof. Pap.*, No. 32, 1905); in Wisconsin, according to Weidman and Schultz (*Wisconsin Geol. and Nat. Hist. Surv. Bull.* 35, *Econ. Ser.*, 1915, p. 50) the rate seldom reaches half a mile a year, is often only a quarter of a mile a year, or less that 4 feet a day, and may be slower. The hydraulic gradient varies with the permeability of the rocks. Thus in one section the descent of the water-table in the first 6½ miles is 74 feet a mile; in the next 16¼ miles it is 10 feet per mile; in the next 9 miles it is 2 feet per mile; during the last 10 miles near the Mississippi the fall again steepens to about 6 feet per mile.

As water percolates underground it usually undergoes chemical changes by loss of its oxygen and carbon dioxide, and the solution of material from the rocks. It may become "hard" by solution of bicarbonate and sulphate of lime, or salt by dissolving common salt, or alkaline by dissolving soda and potash; it may also become charged with iron, magnesia, silica, sulphuretted hydrogen, sulphides, sulphates, etc.

Subterranean waters may become too salt for domestic or agricultural use, but are usually preserved from organic pollution by the purifying action of the soil. The living soil acts as a filter which absorbs the organic matter in water and destroys noxious germs. If the soil is pierced by a pit or cesspool, water may carry germs into an underlying sheet of sand and gravel; all the water may be infected and a widespread epidemic ensue. The disposal of sewage by cesspools, percolation-wells or dumb-wells is therefore dangerous. These wells are shafts sunk into a porous formation, into which sewage is discharged and drains away. Such wells are useful in flat lowlands where there is no surface slope for the drainage. A legal decision in 1885 prohibits the use of such wells where they may contaminate the underground water supply One town is not allowed to pour its sewerage into the bed from which another town draws its drinking water; but the owner of any plot of land has the right, under both British and American law, to draw from it as much water as he can.

WELLS AND SPRINGS—The simplest condition for a spring or well is where a porous bed, such as sand, rests on an impermeable bed. Rain-water percolates into the sand until the water-table rises sufficiently above an outlet to discharge there as a spring. Lines of springs occur along hill-sides where wet sand rests on clay. If an excavation be made at such a position water will flow into it, and it forms a shallow well or *soak*. The traverse of desert countries often depends on the discovery of the right positions at which to dig soaks. They are often beside pools of salt water which remain a foot or so deep where there has been no rain for many months, and evaporation removes 10 feet a year. These pools must be renewed by soakage from adjacent beds. The positions of discharge of the water may be indicated by a few rushes or microscopic algæ on the ground, or on a still day by a slight tremor in the air due to the different refractive index of the moist air. Where the ground is charged with salt the soak will only yield salt water, and a position has to be found where a soak will occur above the salt-charged level.

Soaks give but small yields; for they only occur where the water percolates slowly or the supply would run away quickly, instead of oozing out for months or years. Most wells are similar in principle to soaks, though the water-bearing layer is larger, and contains more water, and the yield is larger and quicker.

FLOWING WELLS—Prolific deep wells often occur (Fig. 59) where a permeable bed passes underground between two impermeable beds. The water that percolates from the outcrop is at length prevented from sinking deeper by the thinning out of the porous bed, or its becoming compact and non-porous, or the increase in temperature, or some obstacle such as a fault or a dyke. If a well be sunk through the overlying impermeable layer, the water will rise in it to a height determined by the pressure-head. If the mouth of the well is lower than the water-charged part of the permeable rock, the water will discharge as a flowing well. If the head of the water does not force it to the top of the well it can be obtained by pumping or baling, or, as in the air-lift pump, by the injection of compressed air, the expansion of which lifts the water to the surface.

One well-known variety of flowing well occurs where a permeable bed is bent into a trough-like fold or syncline

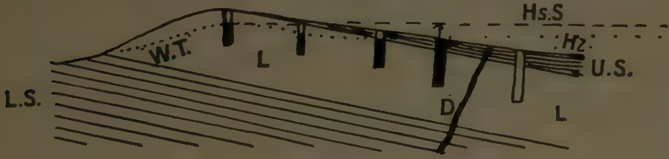

Fig. 59.—Circulation of Water

Circulation of water in a porous limestone, L, between two impermeable beds. U.S., Upper shale, and L.S., Lower shale; D, Dyke; W.T., Water-table if D were absent and the limestone had a discharge at lower end. Hs.S., Hydrostatic Surface, owing to blockage of flow of water by the dyke, D; Hl, Level of Hydraulic Surface if dyke were absent. In the 5 wells the solid part indicates the water-level as it would stand in wells 1-4, if the dyke were absent. No. 4 would be a flowing well; with the dyke present water in that well would rise in a pipe to Hs.S. No. 5 would be dry owing to the dyke.

between two impermeable beds; when the deeper part of the water-bearing layer is reached by a bore the water overflows at the surface owing to the pressure of the water in the upper part of the "U"-shaped sheet of permeable rock. Such wells were called *artesian* from those at Artois in Flanders. The term has been used so widely that it has lost its meaning. It is used in America for all deep wells. In the British well sinking industry it is used for bored wells in distinction to dug wells. Flowing wells due to the pressure of water at a higher level in a water-bearing bed in a synclinal are widespread, as in the London and Paris basins. Flowing wells due to simple water pressure also occur where the beds are inclined in one direction, as along the coast of

Western Australia, and in Dakota and the adjacent parts of the United States.

The London Basin consists of a synclinal of chalk between beds of clay, and when the chalk was first pierced many of the wells flowed at the surface. The water-level has however fallen, and the wells have become "subartesian" or "artesoid," as the pressure only raises the water part of the way and it has to be pumped to the surface. The water-level of the central London wells falls between 1 and 2 feet a year as much of the water is an old accumulation, or is *water of cisternage.* After it is exhausted these London wells will yield only the small supply afforded by percolation of water from the out-crop.

All flowing wells and the flow of oil wells were once attributed to water-pressure. Some flowing wells are, however, due to rock-pressure. Venice stands on a sheet of clay containing lenticles of sand charged with connate water. If a bore enters one of these lenticles the weight of the over-lying clay and city squeezes out the water as out of a sponge. The well flows at first under high pressure, which falls as the lenticle is relieved of its surplus water.

ROCK-PRESSURE—Flowing wells due to rock-pressure may be illustrated by those at Kynuna in Queensland (Fig. 60) (*Econ. Geol.*, ix, 1914, pp. 768-75). The water there comes from 22 thin layers of sand and sand-rock which are interstratified with beds of shale and occur at depths between 270 and 2179 feet. The water from the first water-bearing layer rose only 40 feet in the well; from the next layer, at 420 feet deep, it rose 80 feet; and the rise increased with the depth until from all the layers below 1857 feet the water overflowed from the mouth of the well. The greater the rock-pressure the higher the water rises in the well. Many of the water-bearing layers are so thin that they must be small in extent and the pressure in the Kynuna wells cannot come from water in distant hills. It must be due to a local source, and as the uprise steadily increases with the depth, the discharge is doubtless due to the weight of the overlying rocks.

Rock-pressure may also explain the loss of head and decline in flow of some wells in the Dakota Sandstone. Near Edgeley in North Dakota the hydraulic gradient in 1886 was about 4 feet to the mile; but in the past 40 years it has fallen to 15 feet per mile, and many wells have ceased to flow. The discharge of the water is attributed to the compression of the sandstone by the weight of the over-lying material, whereby the district around Ellendale has subsided 4½ inches. North Dakota in 1921 passed a law (Meinzer and Hard, *U.S.G.S. Wat. Sup., Pap.* 520, 1925, p. 76) prohibiting waste of water from the flowing wells; this Act has reduced the loss of head and will, it is hoped, limit the discharge to the amount renewed by subterranean inflow from the western intake.

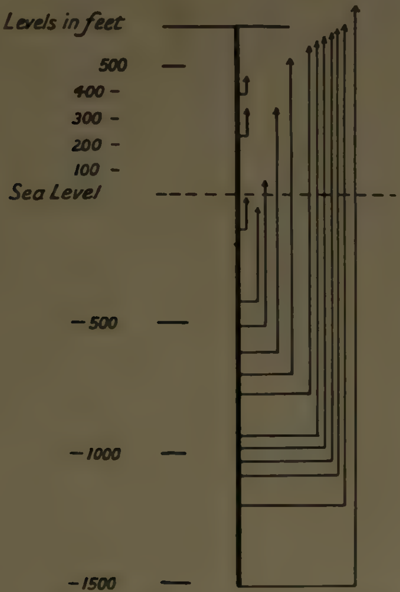

FIG. 60.—THE KYNUNA TOWN WELL, QUEENSLAND.

The ascent of water in flowing wells by the influence of rock-pressure. The well passed through 22 water-bearing layers; the rise of water from each layer increases with the depth, until the water from the depth of 1800 feet discharges at the surface. The water from the lowest beds would rise in a pipe 67 feet above the mouth of the well.

GAS-PRESSURE—Many flowing wells are due to the pressure of their included gases or water vapour, which force the water to the surface like the expanding compressed air in an air-lift pump.

The basin of flowing wells in East Central Australia occupies an area of 602,000 square miles in Queensland, New South Wales, and South Australia. The wells render possible the pastoral use of the country, as the water is good enough for stock, though not for irrigation. The country consists of a foundation of contorted ancient rocks covered to the south by compact fresh-water Jurassic sandstones, and to the north by marine Permo-Carboniferous rocks. The sandstones are covered by clays, limestones, and thin sandstones of the Rolling Downs Formation (Cretaceous). The sandstones outcrop in the eastern part of the plateau at levels of 2000 feet; and they dip westward until in the Lake Eyre basin they are 5000 feet below sea-level. Wells bored into the sandstones yield supplies of water which rise to the surface in places with sufficient force to work turbines for wool scouring and electric light plants. The water is hot, and from many wells its temperature as discharged was above 200° F., and in one well was 210°. The rise of temperature beneath the surface, if the water comes from the level of the bottom of the bore, would be sometimes as rapid as 1° F. for 22 feet in descent; rarely is the rate as low as 1° in 53 feet, which in some parts of the world is regarded as the normal gradient. The high temperature indicates that some of the water reaches the sandstones from a much greater depth than the bottom of the bore. The water is generally rich in alkaline carbonates, including those of soda, potash, lime, and magnesium. It is low in sulphates and sodium chloride. The wells reach a depth of 7000 feet, and some of them gave an initial yield of over 4,000,000 gallons a day, and many yielded over 1,000,000 gallons a day.

The usual explanation was that these flowing wells discharge rain-water that fell on the Eastern Highlands of Australia, percolated through the sandstones from the outcrop, and is forced to the surface by the pressure of the water in the higher part of the bed. It was calculated that the renewal of the well water from the rainfall so greatly exceeded the discharge from the wells that their outflow was relatively insignificant. In 1891 the Lower House of the

Queensland Parliament passed a Bill to prevent waste of this water; but it was rejected by the Upper House on the ground that the waste was immaterial. This simple explanation of these wells is inadequate. The sandstones are often too compact to transmit water readily; the catchment, especially in the northern area, is insufficient as the available intake there, the Blythesdale Braystone, outcrops only in a region of limited rainfall and high evaporation, and is not crossed by any rivers which could discharge large supplies of water into the sandstone. As has been pointed out by Dr. du Toit it would take centuries for water from the supposed intake to reach the western wells. Moreover, many of the water-bearing sandstones are thin lenticular layers which are not likely to be of great extent, and their water cannot be renewed from the supposed intake. The author suggested in 1901 that the well is largely connate water, which had been stored in the beds since their formation, and is partly plutonic water, which contributes the high gas-pressure that forces the mixed water to the surface (cf. *Dead Heart of Australia*, 1906, pp. 271-341; *Geog. Journ.*, xxxviii, 1911, pp. 34-59, 157-81). Numerous hot springs occur to the E. of the basin, and if others discharge under the Rolling Down Formation the water would accumulate in any porous beds or joints at a high temperature. Owing to this plutonic water in parts of the country the well water in places rises above the calculated hydraulic surface; thus at Coomburra, N.E. of Burke, where the water would be raised by water-pressure to only 800 feet, the actual pressure is sufficient to uplift it to 1058 feet. Various groups of wells have also (*Proc. Pan-Pac. Sci. Congr.*, 1923, ii, pp. 1294-5) an abnormally high temperature. These Australian well waters are unusual by their poverty in sodium chloride and sulphates, by being highly alkaline, and by many containing boric acid, which is regarded as indicative of plutonic origin unless it has been dissolved from secondary borates. The chemical composition of these waters is fully consistent with their plutonic origin. In recent years the wells have fallen in yield throughout practically the whole area, the average decrease in all the bores in New South Wales from 1903 to 1908 being 5½ per cent. per annum, and in the wells gauged periodically from 1914 to 1921, the annual decrease was

3·18 per cent. In the Queensland wells the decrease is from 3 to 3½ per cent. per annum. This decrease in yield has been accompanied in some areas by an increase in the corrosive quality of the water, and in some cases by a rise of temperature, in one well amounting to 10° F. in two years. Hence in some parts of the basin the proportion of the plutonic water has increased, showing that some of it is still rising into the water-bearing beds.

Town Supplies and Settlement—Early settlements are usually limited to areas where there is an available supply of water either from a river or lake or from shallow wells in sand or gravel. Clay in thick beds is only available for residence after a water supply is provided by pipes or aqueduct. London, for example, drew its water from the Thames nearby, until the supply became too impure for domestic use. The suburbs were limited to areas of gravel, for wells in London Clay had to go through it into the underlying sands and chalk, and were too deep and costly for single dwellings. Cities depend for their water either on deep wells or on supplies brought from outside either from rivers or lakes.

London now draws its main supply from the Thames above the area affected by the tide. In summer the flow of the Thames over the lowest lock at Teddington is often only 200 million gallons a day, and has been as low as 154 million (August, 1887). Hence as London needs an average from the Thames of 230 million gallons a day, it would require sometimes more than the total flow; and the flow in the Thames must not be reduced by withdrawal to less than 100 million gallons a day. Hence if London depended on a supply drawn daily from the Thames it would often be thirsty. Winter floods discharge as much as 7500 million gallons a day. Supplies are then collected in immense storage reservoirs, which are available for use throughout the year. This system has the advantage that the water is improved and purified by storage; noxious germs are destroyed, and the water is rendered innocuous.

Cities near mountainous country draw supplies from lakes or artificial reservoirs, for the rainfall is usually high and the run-off carries a high proportion into the reservoirs. Glasgow was the pioneer of this system by, in 1859, drawing its supply from Loch Katrine; Manchester obtains its water from Thirlmere in the Lake District, and Liverpool and Birmingham their supplies from artificial lakes in Wales.

Reservoir Sites—The site of a storage reservoir needs careful geological survey to avoid loss by percolation and to secure safe foundations for the dam. Sandstone and limestone are unsuitable, for their permeability may lead to serious leakage. Loss of water through a thin porous bed can be prevented by a puddle trench—a deep trench beside the dam filled with packed clay or concrete. Faults may lead to loss of water and render the foundation of the dam insecure. The reservoir must also be provided with an adequate overflow channel to discharge any sudden inflow of water as from a cloudburst. Few catastrophies reek such complete devastation as the rush of water through a broken dam.

CHAPTER XX

COAST DEFENCE, COASTAL WORKS, AND RECLAMATION

Waves and Wave Action—The remorseless attack of the sea has devoured wide tracts of coastland by marine abrasion, which is mainly the work of the waves. Their power depends on their size and speed. The length of a wave is the distance from crest to crest; the height is the difference in level between the crest and the bottom of the adjacent trough; the amplitude is the height of the crest above the average level of the water. A wave appears to be an advancing ridge, but that aspect is often as delusive as with the waves that sweep across a wheatfield as the stems sway before the wind. In waves of oscillation the particles of water revolve around a stationary point, and do not move forward; in waves of translation the particles advance as well as revolve. Waves of oscillation occur in the open sea, where the depth of water is greater than the length of the wave. Where the depth is the less, the movement on the lower side is retarded by friction with the floor, and the particles move forward in the upper part of the circuit further than they go back in the lower part, and the water advances as a wave of translation. It has been objected, as by B. Cunningham (*Harbour Engineering*, 1918, p. 164), that in practice the distinction between waves of oscillation and of translation is artificial, as all sea waves cause some advance of the water. When the wave reaches shallow water the crest advances more rapidly than the base, and the front is fed with water more slowly than the back; hence the wave curls over, and falls as a breaker. Waves on a beach are waves of translation; and the backward and forward movement gives the water its power of attack.

The greatest oscillatory waves are in the Southern Ocean and are about 50 feet high. In the North Atlantic the maximum is about 40 feet. Vaughan Cornish (*Waves of the Sea*, 1910, p. 53), during a strong gale in December, 1900, measured many waves 29 feet high, and some of 43 feet. The height depends upon the "fetch," i.e. the width of open water to windward; if the fetch is more than 39 miles the height of the waves (H) in feet is one and a half times the square root of the fetch (D), i.e. $H = 1{\cdot}5\sqrt{D}$; if the fetch is less than 39 miles $H = 1{\cdot}5\,(2{\cdot}5 - 4\sqrt{D})$. The heights of waves, according to the formulas, are as follows:—

Fetch.	Wave Height.	Fetch.	Wave Height.	Fetch.	Wave Height.
1 mile	= 3 ft.	30 miles	= 8 ft. 4 in.	100 miles	= 15 ft.
10 miles	= 5 ft. 6 in.	40 ,,	= 9 ft. 5 in.	200 ,,	= 21 ft. 5 in.
20 ,,	= 7 ft. 1 in.	50 ,,	= 10 ft. 6 in.	300 ,,	= 26 ft.

The waves in Lake Geneva are 8 feet high where they have a fetch of 40 miles, those on Lake Superior 20-25 feet high with a fetch of over 300 miles.

The depth of disturbance of a wave is equal to its length; the maximum length of ordinary waves in the Atlantic is 600 feet, and they disturb fine sediment to the depth of about 600 feet or 100 fathoms. The action diminishes rapidly with depth. The displacement of water particles at a depth equal to the length of the wave is only $\frac{1}{535}$ and at double that depth is only $\frac{1}{286690}$ of that of the surface. At special points waves and currents move material far below the ordinary limit of wave action. Lobster pots in the English Channel are sometimes filled with coarse shingle at the depth of 180-200 feet. Seaweeds which live not less than 200 feet deep are washed ashore with stones attached to their roots, and must have been torn from the sea-floor by waves. The cover of telegraph cables is cut by drifting sand at the depth of 600 feet, and silt is moved at greater depths.

The transport of beach material depends on the angle at which waves strike the shore. A wave which rushes obliquely up the beach returns by the shorter steeper course at right angles to the shore; it carries material along a zigzag course. The backwash may be concentrated and strike a more powerful blow than the oncoming wave; thus at Dunbar a wave which struck with a force of 7 cwt. per square foot in its advance, on its recoil gave a blow of 1 ton per square foot. The backwash by its undercurrent carries beach material outward.

Swiftly moving water is a most powerful disruptive agent, for its blow is heavy and it attacks the weakest point like a pickaxe. The force of waves was measured in 1843-5 by Alan Stevenson when designing the lighthouse at Skerryvore, a low rock 12 miles from the coast of Tiree (Alan Stevenson, *Skerryvore Lighthouse*, 1848; Thos. Stevenson, *Lighthouse Construction*, 1881). The average wave during the five summer months struck a blow of 611 lb. per square foot; the average for the six winter months was 2086 lb. per square foot; the maximum in a gale, 29 March, 1845, was 6086 lb., or nearly 3 tons per square foot. In narrow seas the wave force may be as great. Thus on the eastern coast of Scotland blows of 3 tons per square foot have been measured at Buckie, and of 3½ tons per square foot at Dunbar.

The height reached by waves varies with the slope of the sea-floor and the shape of the land. Thus at the Fastnet Lighthouse, off South-western Ireland, a chasm acts as a nozzle and water is flung against the tower at the height of 120 feet, and a 3-ton block of stone was thrown off the cliff at the height of 82 ft.

The direct blow of the waves tears away and shatters masses of hard rock. During the construction of the breakwater at Wick a mass of concrete, 1350 tons in weight, was moved from its place. A storm at Genoa in 1898 swept the base of the breakwater bare of shingle, undercut it, and carried for 155 feet blocks of concrete 600 cubic feet in volume, and weighing 40 tons. A storm at Bilbao in 1894 swept away the huge blocks of stone placed to shield the breakwater which was breached, and one mass of 1045 cubic yards and weighing 1700 tons was carried 175 feet into the harbour.

Recession of the Land.—With such effects on carefully built structures, it is not surprising that the sea rapidly wears away soft rocks. Waves hurl beach material against a cliff, and its fragments serve as ammunition for its further destruction. The cutting back of the land is aided by air being compressed in cracks and crevices in a cliff by an advancing wave, and on its fall expanding with explosive violence. This effect was discovered by the first Eddystone Lighthouse (1700). The door had been strongly supported to resist the waves, but it was blown outward by the expansion of air compressed within the lighthouse.

The wearing back of the coast is aided by subaerial denudation, which generally produces an upward slope inland above the sea-cut part of the cliff.

Wave action is aided by animals and plants. Seaweeds growing on a rock enable a wave to move it. Animals bore into rocks and their acid secretions dissolve the cement; Pholas bores into limestone; the shipworm, the Teredo, burrows through timber; and sea-urchins (Echinoidea), browsing on films of seaweed, wear pits even in granite.

Transport of Beach Material—The material obtained by the wearing back of a cliff is rolled to and fro by the waves and reduced to shingle, which drifts along the shore. According to one view this movement is due entirely to waves made by the wind; but according to another it is due to tidal currents. Both agencies act in varying degrees; the movement of pebbles is usually by the waves, but guided by the persistent currents. Beach shingle and river shingle may be distinguished by the shape of the cobbles (stones of about 4 to 5 inches in diameter), which in a river are rolled along with the long axis at right angles to the current, and are typically ovoid. Cobbles on a sea-beach are spun around by the tide, the base is worn flat, and the upper side is rounded by the scour of sand, until they become bun-shaped.

Marine abrasion forms a shelf or plain of marine denudation between high and low tides. "Stacks" or pillars of hard rock may rise above it. The "Old Man of Hoy" in the Orkneys is a pillar of Old Red Sandstone about 450 feet high. Some bands of rock with the layers on end and lying in contorted shale were attributed to glacial action, until Murray Macgregor recognized them as stacks that had fallen on a muddy shore.

Sea-caves are formed where rocks are eaten into hollows. Raised lines of caves often give evidence of the uplift of a coast.

Continental Shelf—A broad shelf of mud, sand, and shell beds with occasional exposures of rock, borders the continents and extends from the shore till, at the depth of from 50-100 fathoms, the sea-bed begins its long descent to the oceanic floors. This shelf has been regarded as either a great plain of marine erosion, or a submerged peneplane; but it is too wide and deep to have been cut by the tide, and is more regular and extensive than any peneplane. The explanation has been given by Nansen, who attributes the shelf to waves spreading loose material evenly over the sea-floor, filling up depressions, and wearing down rock ridges.

Rate of Marine Abrasion—The rate of marine abrasion varies with the strength of the rocks and their exposure. The loss of land on the southern coast of Yorkshire is estimated at 3 yards per annum for the past century, and a total of 3½ miles since Roman times. A British Association Committee on Coast Erosion reported in 1895 that the Yorkshire coast during the 37 years, 1852-89, had lost 5 feet 10 inches per annum. The recession is also rapid at exposed positions in Norfolk and Kent. The question whether this process is a national danger was investigated by a Royal Commission on Coast Erosion (1906-11); the evidence proved that the British Isles gain from the sea more than they lose. In the 35 years, 1848-93, 774 acres were lost on the Yorkshire coast, but 2171 acres were reclaimed within the Humber. The cliffs in Southern-eastern Yorkshire are so high that for every square yard lost 3 square yards are gained by the redeposition of the material elsewhere; as the new land is Crown property the gain is national. The total loss to the United Kingdom between 1848 and 1893 was 6640 acres; but over 49,000 acres were gained.

Subaerial erosion, though less spectacular than marine abrasion, has greater effects. Subaerial lowering of the land has been estimated at about 1 foot in every 10,000 years; the British coasts undergoing abrasion probably do not lose on an average more than 5 feet a century. The average height of England is about 650 feet. Hence the whole land would be reduced to sea-level by subaerial denudation in 6½ million years, during which marine abrasion would have removed a strip 65 miles wide, from part only of the coast.

Coastal Accretion—The land may be extended seaward by the formation of beaches, bars, and deltas, and the filling of bays and estuaries. The first stage in the filling of a bay is usually the formation of a bar, which is a bank joined to the land at each end, or of a spit, which is joined at only one end. The most typical spit in the British Isles is Spurn Head, which is due to the transport of pebbles southward along the Yorkshire coast; it is 10-20 feet high, and 2½ miles long, of which 1½ miles have been formed since 1676.

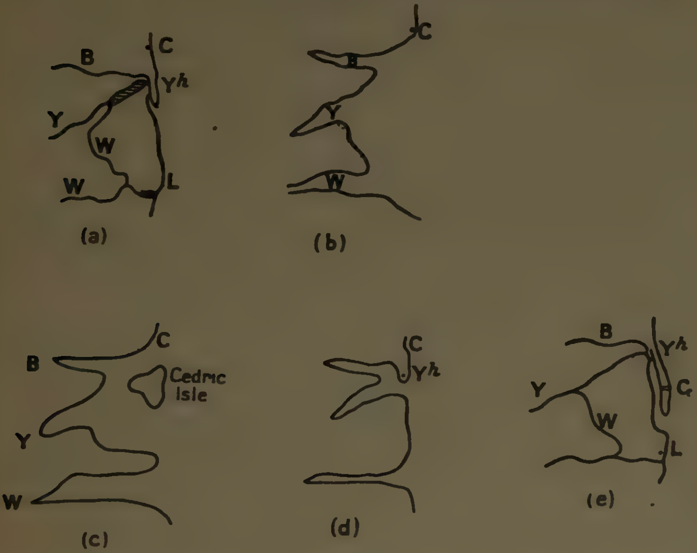

FIG. 61.—THE CHANGES IN THE BURE (B), YARE (Y), AND WAVENEY (W) ESTUARIES.

(*a*) Present course of the rivers; the Broads are marked by horizontal lines. (*b*) The condition of the estuary in Roman times. (*c*) The condition in Saxon times with the formation of Cedric's Island. (*d*) In Norman times with the beginning of the formation of the Yarmouth (Y*h*) Spit. (*e*) The extension of the Yarmouth Spit towards Lowestoft (L) with the mouth artificially cut at Gorleston (G). C, Caistor.

It formerly grew southward from 20-56 yards a year, but from 1873 to 1902 the rate has been only 3-4 yards a year as the movement of the shingle has been checked by groynes. The spit is worn away along the sea-front and enlarged by deposits of silt on the inner side, so that it is slowly moving westward. Ravenspur, a Danish settlement which is now under the North Sea, stood on the western side of the Spurn Head of its day.

The effect of spit formation in a less powerful river than the Humber is shown by the Yare,[1] which in Roman times had a wide opening to the North Sea (Fig. 61 *a-e*). A shoal formed across the estuary, and had become an island by 495, when the Saxon, Cedric, landed upon it. Its growth into a large delta left the Yare with two mouths. The southward drift of shingle closed the northern mouth after 1066. The filling of the estuary by silt diminished the tidal flow, which no longer stopped the southward growth of the spit; by 1347 the spit extended 10 miles S. of Yarmouth and the Yare mouth was near Lowestoft. The Yare frequently breached the spit until a channel was cut in 1560 at Gorleston, and has since been artificially maintained. The southward migration of the shingle then ceased, and the spit from Gorleston to Corton was swept away as the material was not replaced.

WARPING—THE SILTING OF ESTUARIES[2]—Silting in the stagnant water behind a bar or spit converts an estuary into land. The salt in the sea promptly precipitates the silt carried into it by rivers. If fresh water be stirred up with mud, it remains turgid far longer than salt water. The salt coagulates the particles of silt, which become larger and heavier, and sink more quickly. The mud banks thus formed are raised above tide level; their rise is aided by vegetation, which acts as a sieve and catches the sediment carried against it.

The lowland beside an estuary may be raised by warping, as more silt is carried on to it by the rising tide than is removed by the gentler ebbing water. Each tide deposits a thin film of "warp." Carey and Oliver report (*Tidal Lands*, 1918, p. 212) that 184 acres along the Trent were raised by warping from 1-4 feet in 3 years; grass was grown on the land at the end of the first season, and in the fourth year it yielded large crops. Natural warping along the Norfolk coast near Blakeney (*ibid.*, pp. 200-1) varied from 1 foot in 9½ years to 1 foot in 120 years, in a position only

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[1] For recent study of the coast of East Anglia, J. A. Steers, *Geogr. Journ.*, 1927, lxix, pp. 24-48.

[2] A. Beazeley, *Reclamation of Land from Tidal Waters*, 1900.

reached by water which had dropped nearly all its silt elsewhere.

The filling of an estuary or lake may be aided by silt-jetties being built up by rivers, which deposit their silt as a bank in the stagnant water on each side of their entrance. Banks thus formed are slowly raised above the water-level as silt-jetties. The delta of the Mississippi with its finger-like projections has been thus extended into the Gulf of Mexico. Silt-jetties subdivide where a river bifurcates against an obstacle, and the junction of adjacent jetties breaks up an estuary into separate lakes; the river twists and winds between these lakes, though separated from them perhaps only by a narrow swampy bank. The Norfolk Broads are typical examples of this formation. They were originally part of an estuary, which has been silted up owing to the narrowing of its mouth by the Yarmouth spit, and divided by confluent silt-jetties into shallow lakes. The borders extend inward and the lake is reduced to a small round pool; and its disappearance completes the conversion of the estuary into an alluvial plain.

Coastal Protection by Planting and Groynes—Strong masonry has been often used as defence against the sea. It however may be undercut and out-flanked, and its fall provides ammunition by which the waves more effectively batter the coast. William Smith,[1] the Father of Geology, was sent in 1801 to the Norfolk coast to devise means for its protection; he carefully observed wave action and condemned masonry as dangerous; he recommended "embankments as like as possible" and of the same materials as those thrown up by the sea. They by their looseness disarm the waves, and provide permanent and cheap defence. Sand dunes are effective protection but they may be blown away by the wind. Their migration can be stopped by such plants as Marram grass, *Psamma arenaria*. Its long underground stems and roots form a firm mat and the spikes of grass stop the movement of sand grains on the surface. A growth of Marram grass converts a moving into a fixed dune. It may thereby defend a coast from the sea, and save a fertile plain from being overridden by sand dunes from an adjacent desert.

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[1] J. Phillips, *Memoir Wm. Smith*, 1844, pp. 50-3.

Shingle beaches similarly protect the shore. The shingle travels along the coast at a rate that can be measured by placing a load of bricks upon the shore and observing their drift month by month. If the shingle of a beach is renewed it affords a permanent defence. Coast protection in many places depends on prevention of the migration of shingle. The simplest method is the use of groynes, or "horses," which are barriers of timber, masonry, or cement, built across the beach. Well-placed groynes hold the beach material and protect the coast beside them; but by retaining the shingle that would renew the beaches further along the coast they lead to more rapid erosion elsewhere. It was reported to the Coast Erosion Commission (*Rep.* iii, 1911, p. 110) that groyning the English coast would, in 1911, have cost £300 a mile, with the result that for every acre saved another would be lost elsewhere. Groynes are useful in protecting important positions; but they endanger adjacent land.

The design and size of groynes should be adjusted to the local conditions. The system designed by E. Case for Dymchurch in Romney Marsh on the coast of Kent, is based on the principle that the main drift is between mean sea-level and low tide; hence low groynes rising two or at most 3 feet above the lower part of the beach are adequate, as they stop nearly all the drift and secure a slope at the natural angle of repose.[1] Groynes are usually placed at right angles to the beach; but they may point leeward. If placed too close together groynes raise the water-level, and increase the backwash and thus hasten the transport of material down the beach.

Harbour design is affected by some of the factors which control the efficiency of groynes. The most convenient site for a harbour is usually an estuary, where the river current or tide can be used to keep the channel clear. Some former British ports have been closed by silt. Chester was the chief port of the Western Midlands until the silting of the Dee estuary diverted the trade to Liverpool. London has maintained its position as a port, owing to the well-designed

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[1] Ed. Case, *Rep. Brit. Assoc.*, 1899, p. 859; J. S. Owens and G. O. Case, *Coast Erosion and Foreshore Protection*, 1908.

measures to maintain and deepen the new channel of the Thames.

The chief difficulties of an estuarine port are the silting of its channel and shoaling at the entrance. The channel may be maintained by dredging or by the automatic scour of the tidal current. On an open coast the only available method of harbour construction may be a costly breakwater, which, if ill-designed, is ineffective. Thus the breakwater at Ceara in Brazil (Fig. 62) was connected with the shore by a viaduct, in the hope that the stream under it would scour the harbour ; but in 20 years sand had filled the basin and carried the foreshore almost to the end of the breakwater.

Sea-Walls—Masonry may be weakened by the chemical action of sea-water on concrete, for the sulphate and chloride of magnesia alter any unstable form of lime into calcium sulphate and chloride, which are removed in solution. These reactions happen if the concrete contains an excess of lime, and the trouble can be avoided by preventing the entrance of sea-water, or by the addition of material such as trass or brickdust or ground slag, which will combine with the free lime (D. B. Butler, *Portland Cement*, 3rd edition, 1913, p. 374).

Fig. 62.—The Ceara Breakwater, Brazil.

Shoaling of the Ceara Breakwater, Brazil, built 1884. The four dots at the lower end of the Breakwater represent the piers of the viaduct. S.L. 1884, and S.L. 1903 represent the shore-lines in 1884 and 1903. L.W. 1884 and L.W. 1903, low water at the same dates.

Sea-walls, if perpendicular, are struck with the full force of an advancing wave and may be undercut. If the foot projects in a curve the wave is checked gradually ; a slope of one vertical in ten horizontal is often adopted as it is usual in shingle banks. A projection along the top of a sea-wall is sometimes used to throw back the spray ; but as this coping is subject to heavy upward blows it is liable to crack the wall.

Estuary Works and Models—The conditions of estuaries are so complex that the effects of a change cannot always be foreseen. Models show the effects of projected improvements on tide and current, and have been often used since their introduction by L. F. Vernon Harcourt for the Seine (*Proc. R. Soc.*, xlv, 1889, pp. 509-20) and the Mersey (*ibid.*, xlvii, 1890, p. 142; *Rivers and Canals*, 2nd edition, 1896).

The problems of coastal defence and harbour improvement are so varied that each case has to be judged by application of the principles of wind and current action to its special geographical circumstances, so that the scour may be adequate but not excessive, and may act where it is wanted. Any interference with the natural agencies may upset their balance and have disastrous consequencies unless all the possibilities have been carefully considered.[1]

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[1] D. W. Johnston, *Shore Processes and Shore Line Development*, 1915; F. Latham, *Construction of Roads and Sea Defences*, 1903; E. R. Matthews, *Coast Erosion and Protection*, 1918; Thos. Sheppard, *Lost Towns of the Yorkshire Coast*, 1912; W. H. Wheeler, *Sea Coast*, 1902.

CHAPTER XXI

EARTHQUAKES AND PRINCIPLES OF ANTI-EARTHQUAKE CONSTRUCTION

The Nature of Earthquake Action—The earth's crust is in constant tremor. The earth travels along its orbit 3000 miles a minute, and places near the Equator revolve around its axis 1000 miles an hour. As the crust is irregular in structure it is always quivering like a badly mounted flywheel. The surface is affected by continual variations in temperature, in the weight of the atmosphere, in the distribution of snow, rain, and tidal water, by blows on hillsides from the wind, the hammering of surf on the coast, and the slip of material down hills and oceanic slopes. The crust is violently jerked when blocks sink owing to the loss of support, or slide over one another under the lateral pressure of the contracting crust. All these agencies produce waves of distortion, which range from tremors perceptible only by the most sensitive instruments, to shocks which devastate a province and slay a hundred thousand people.

The Greeks knew that an earthquake spreads radially from its place of origin, which Aristotle called the *centrum*. The term is convenient though the centrum may be a large area and not a point. Above the centrum is the *epicentrum* or *epifocal area*, where the vibration emerges up the *seismic vertical*. Around the epifocal area the *angle of emergence* decreases outward, and is recorded by cracks in masonry or plaster, which tend to be normal to the earthquake path. Lines representing the angles of emergence converge to the centrum.

The epicentrum may be determined from the times at which an earthquake was felt at different localities. *Homoseists* are lines joining places shaken at the same time. *Isoseists* are lines through places where the shock was of equal severity. The *meizoseismic* area is that of the greatest disturbance, which is not always the epicentre as, the vibrations there being vertical, may have little overthrowing effect. Away from the centre, as the angle of emergence of the waves become less, the horizontal component in the vibrations becomes larger and more destructive, until it gradually loses strength. The meizoseismic area or zone is where the combination of angle of emergence and strength of shock has the greatest destructive power.

The determination of the source and cause of an earthquake requires a map of its range. Homoseists are easily drawn where there are many daily rated clocks, as along railways and telegraph lines. Where time records are unreliable isoseists are used, as they are based upon facts and experiences that can be observed and verified afterwards. Earthquakes are classified according to intensity by the ten grades of the Rossi-Forel scale: (1) light tremors recorded only by seismographs; (2) noticed only by a few people at rest; (3) felt by most people who are awake but lying down; (4) felt by people in motion, light objects moved, and plaster ceilings cracked; (5) felt universally, furniture moved, and light mechanically swung bells rung; (6) awakens sleepers, rings most bells, stops clocks, swings chandeliers, and shakes trees; (7) a "strong earthquake," overthrows objects, rings heavy church bells, causes general alarm, and does considerable damage; (8) overthrows chimneys and cracks walls; (9) characterized as "violent," destroys buildings; (10) a "catastrophic earthquake," complete devastation throughout a large area.

Depth of Origin—Hypotheses as to the structure of the earth's crust led to the view that earthquakes are of shallow origin, and arise at a depth of generally not more than 5 or 6 miles, and probably never more than 10 miles. This conclusion is improbable as a shallow movement would not be likely to devastate an area hundreds of miles in diameter. The Charleston Earthquake of 1886 was of extreme severity throughout a region 1500 miles across, where any widespread horizontal earth-movement is improbable; its range appears inexplicable if its origin was at the depth assigned of only 10 miles. In 1917 the late G. W. Walker, from the angles of emergence of world-shaking earthquakes at Pulkova, concluded that they start from depths down to 800 miles

(*Rep. Brit. Assoc.*, 1917, pp. 13-14; 1922, *Phil. Trans. A.*, vol. 222, pp. 45-6). Prof. H. H. Turner, from the time of arrival of an earthquake shock at the opposite side of the earth, assigns the centrum of most earthquakes to a depth of about 145 miles, and some to 310 miles; e.g. the Formosa Earthquake of 14th April, 1906, started at a depth of 280 miles (*Rep. Brit. Assoc.*, 1922, p. 255), and that in China on 16th December, 1920, at more than 80 miles (*ibid.*, p. 256). The Assam Earthquake of 12th June, 1897, which had a meizoseismic area of 150,000 square miles, was at first referred to a depth of 5 miles, but is now assigned by R. D. Oldham to the depth of between 100 and 200 miles (*G.S. India, Mem.* xlvi, pt. 2, 1926, p. 62).

Causes—Certain unstable belts in the earth's crust are especially liable to earthquakes, which are of three kinds—tectonic, volcanic, and those due to variations in the load on the surface. Tectonic earthquakes are due to unequal movements of the material within or below the crust along great faults and thrust-planes, around subsidences, and along folds which are often traversed by cross-faults. Volcanic earthquakes are due to the uprush of steam during eruptions which keep the adjacent ground in constant tremor, while single explosions may shake the whole world. Volcanic action often results in local earthquakes by the collapse of cavities left by the ejection of material or the shrinkage of the cooling rocks. Such earthquakes may be of intense violence, but of short range; those in Ischia from 1881-3, due to subsidence in an extinct volcano, though they culminated in the destruction of the chief town of the island, were barely perceptible in Naples 18 miles away, and were not recorded in Vesuvius Observatory at the distance of 25 miles.

Earthquakes have been attributed to landslips, such as the Pamir Earthquake of 1911; but Oldham (*Q.J.G.S.*, lxxix, 1923, pp. 243-4) has shown that the landslip at Usoi was not at the epicentre and was a result of the earthquake and not its cause. The slide of material down oceanic slopes often breaks telegraph cables; but the movement may not be recorded by seismographs and so does not cause appreciable vibration in the crust, although the repeated blows of the surf on the coast of India disturbs the seismograph at Calcutta 500 miles away.

ECONOMIC SEISMOLOGY

Earthquakes are of interest to academic geology from the light they throw on the internal structure of the earth. They concern economic geology as regards building design, the recognition of situations liable to them, and their possible prediction.

A. EARTHQUAKE PROBABILITY AND PREDICTION—The imminence of earthquakes may ultimately be foreseen from their distribution in time and space, or observation of their causes. A great shock results from the release of the crust from gradually increasing stress, which might be recognized by slight movements before the catastrophe. The slow tilting of a waterpipe across a line of suspected movement might give warning of an approaching shock.

Earthquakes are most numerous in winter when atmospheric disturbances are usually most violent, and the breaking of a strained belt in the crust may be precipitated by a sudden change in air pressure. Thus the earthquake which devastated Yokohama and Tokyo in 1923, occurred during the passage of a violent cyclone which cannot have caused, but may have hastened the disaster.

A long period without serious earthquake shock need not imply permanent immunity. The eastern coast of North America experiences severe shocks at distant intervals, such as those at Charleston in 1886, and on the Lower St. Lawrence in 1925; and any part of that line may be badly shaken after centuries of rest.

A map of the world showing the distribution of earthquakes shows that they are most frequent in areas of recent earth-movement, and along persistent faults.

Earthquake warnings may be of great service since secondary consequences that might be avoided if foreseen are often the most disastrous. The Lisbon Earthquake of 1st November, 1755, was not of the greatest severity, for parts of the city built on limestone and basalt were not damaged (Sharpe, *Proc. G. Soc.*, 1838, No. 60, p. 36). The heavy death-roll was due to a wave 50 feet high, which swept up the Tagus and drowned the 60,000 people who had taken shelter on the mole. According to tradition the mole was swallowed by an unfathomable abyss; but probably its foundations had been weakened by drainage when the water was withdrawn from its front during the advance of the earthquake wave, and it slid down the mud slope into the river. The Lisbon Earthquake was recorded in France only in the extreme S.W.; but it has been assigned an unusually wide range as a shock in Derbyshire has been attributed to it, but was doubtless due to an independent local earthquake.

Along earthquake stricken coasts most of the destruction is often wrought by a huge wave which rolls in from the sea. Harbours and coast towns in seismic belts are only safe if sheltered from the open sea, or above the reach of earthquake waves.

Some strongly constructed buildings collapsed during the San Francisco Earthquake in 1906, as they were erected on land made by filling bays with loose material, and the weak foundations had given trouble before the earthquake. Similar buildings on firm ground were only shaken, though some were destroyed by fire.

The most fatal earthquake for which there are accurate records was at Tokyo on the 1st September, 1923; the official roll of killed and missing is 142,807. The shock there was moderate; well-built masonry buildings and even fragile structures on their roofs were not injured. The loss of life was due to the earthquake happening just before the midday meal; the charcoal braziers used for cooking were overthrown; fallen laths and scraps of wallpaper were ignited; and many fires broke out simultaneously. The people flocked for shelter into open spaces where they were suffocated by smoke. The damage at Tokyo was estimated at £1,000,000,000, of which 95 per cent. was due to fire.

B. Anti-Earthquake Construction—No ordinary building can resist the most violent grade of earthquake without serious damage. In the Assam Earthquake of 1896 Shillong was jerked 18 inches to and fro 200 times a minute. Walls were shaken to pieces and the roofs settled down over piles of broken masonry. Tree trunks were snapped across just above the ground. This terrific oscillation was combined with an upward jerk by which huge stones were hurled into the air, at an angle of over 60°; after rising 4 feet they struck the ground 6½ feet from their original position.

Similarly in the earthquake of 1923 motor cars at Yokohama were tossed into the air and fell upside down, and houses near the edge of a cliff were flung over it.

Fortunately the meizoseismic area of most earthquakes is comparatively small. The main damage in districts farther from the origin is due to the yielding of insecure foundations, to the collapse of buildings of unsuitable design, or to fire or earthquake wave.

Anti-earthquake building design has been based upon two opposite principles. The first aims at keeping the structure so light and elastic that it withstands shaking like a basket; the other plans a structure so firm and rigid that it is as difficult to shake to pieces as a box. The basket system was tried in Japan, but was unsatisfactory, as though the building was safe, the play of the framework cracked the plaster, overthrew light objects, and created terrifying noise and dust. Extreme rigidity has been secured by interlocking bricks and strong ties, which must be broad to prevent them cutting the structures attached to them. Thus in 1880 a fire destroyed part of Yokohama, and left the brickwork chimneys as isolated stacks. They were uninjured by a subsequent earthquake, when adjacent houses were destroyed by the fall of the chimneys, which were cut through by the bands that attached them to the floors.

C. Loose *versus* Firm Foundations—There has been much discussion as to whether a loose or firm foundation is the safer. A loose foundation may absorb the shock. Milne found that the vibration caused by the fall of a weight of 2000 lb. from a height of 35 feet on to soft ground was barely perceptible 40 feet away, whereas the same blow on hard clay produced a dislocation of about $\frac{1}{280}$th of an inch at 250 feet away. In the Tokyo Earthquake of 1923 of buildings on hard soil only 6 per cent. collapsed, as against 10 per cent. of those on soft soil; but on hard soil 88 per cent. suffered some injury as against 81 per cent. on soft soil.

Many attempts have been made to protect buildings from earthquakes by a free foundation. As Japanese lighthouses suffered from the scattering of oil from the lamps during earthquakes Stevenson designed a lighthouse resting on a platform of cannon balls, hoping that their movement might absorb the vibration. The lighthouse was freed from the lateral vibration of earthquakes, but was disturbed by the vertical shocks and swayed badly in the wind. Milne mounted a room on a layer of cannon balls; it also rocked unpleasantly during high wind; but when the cannon balls were replaced by shot a quarter of an inch in diameter, the friction was enough to resist wind action, and the room remained at rest during earthquakes which caused violent oscillation in the adjacent ground. Milne concluded that the method is practicable for special purposes, but not for ordinary buildings.

The defect of a free foundation is that though the oscillation is reduced in speed, the amplitude and actual movement may be increased. Weak beds generally form unsatisfactory foundations as their cavities collapse and loose patches become more closely packed. The insecurity of weak foundations can be overcome by tying all parts of the building together, so that it moves as a whole. The Temple of Diana at Ephesus is said to have been built on a marsh to protect it from earthquakes. It like other Greek temples was built on a massive platform that acted like a pontoon and protected the superstructure from waves in the foundation. This principle has been adopted by building regulations in earthquake areas; after the destruction of Casamicola in Ischia in 1883, it was enacted that each house must stand on a platform of masonry or cement 27 inches thick for a one-story and 47 inches for a two-story building.

Loose foundations on steep slopes are dangerous, as earthquakes there cause landslips; and the free vibration of the sides of a railway embankment may shake it into piles of sand.

Effects of Lateral Movement—The lateral movement of the surface in an earthquake dismantles railways by jerking the rails forward and buckling them into serpentine curves; bridges are broken by the girders riding forward, till one end falls off its pier. Bridges may also be destroyed by the vertical upward movement thrusting the piers through the roadway, which is dragged down by the descending movement; this process is repeated and the roadway is transfixed by the piers.

Buildings beside steep hill-sides and cliffs are often seriously damaged owing to the free movement on the hill-face. A wave traversing a plateau causes the particles to oscillate about their original position; but at the end of the plateau the ground is flung forward, just as a tap on one end of a row of billiard balls sends a wave through them but only moves the last, which is jerked forward.

Structures should be light to reduce both inertia and momentum; for on a sudden shock inertia tends to jerk the lower part from under the slower upper part; while momentum causes the upper part to continue the forward swing after the base has begun to move back. Hence factory chimneys are built with a broad strong base, which tapers upward, and the upper part is composed of sheet iron, to reduce the weight. A chimney built as a uniform cylinder would be fractured at the base. The danger of top-heavy chimneys was shown at the Warnambool earthquakes in Victoria of 1903; they are built of a dune limestone which is used in thick slabs and the weight of those at the cap rendered the chimneys as unstable as an inverted pendulum and many were overthrown.

The strength of a wall is reduced by the doors and windows, for they serve like the perforations in a sheet of stamps, and the cracks run from one to the next. A medium angle of emergence is accompanied by cracks that radiate from the window corners, while a horizontal emergence is marked by vertical cracks. Vertical rows of windows are weaker than a diagonal or quincuncial arrangement.

The arch is a dangerous structure in earthquake areas unless embedded underground; for during horizontal movements the two sides may move in opposite directions at the same time, and the arch be torn asunder. The Kiso Sawa railway bridge in Japan rested on piers of masonry 26 feet long by 10 feet thick, each supported by two circular drum curbs, 12 feet in diameter. The bridge was destroyed by an earthquake, as the differential movement of the two drums tore each pier in twain; they were replaced by single drums 30 feet by 12 feet.

The reduction of the stresses due to momentum and inertia specially concerns the design of roofs. When a building is jerked forward the roof tends to remain behind, and the side left unsupported may fall into the room. In Japanese temples the roof timbers were knit together by many joints which yield slightly, so that the stress is spread widely and not concentrated at one level. Closely knit iron girders give the same firm but flexible connection between roof and walls. The roof can also be supported on posts that rise from a platform of stonework or cement, which forms the sole-plate of the building; the posts are connected by cross-beams and rafters, and as the roof moves with the ground, there is less tendency to horizontal fracture. The roof should have a gentle slope, or the tiles may be shaken off. The leverage of the roof is less on low than on tall buildings; hence in some earthquake areas houses are restricted to two or three storeys. Doubts have been expressed as to the safety of American sky-scrapers with their 35 or 50 stories; but these buildings have the advantages of strong construction and a firm foundation.

LEVEL OF GREATEST DAMAGE—A building when disturbed by an earthquake, away from the epicentre, sways like an inverted pendulum with a period dependent on its height. The level most liable to damage depends on the rate of vibration of the earthquake and the oscillation period of the building. If the latter be the longer the upper part tends to continue its sway forward while the lower part has begun to swing back, and a rupture may occur between the parts moving in opposite directions. Thus in the San Francisco Earthquake of 1906 a tall building 20 storeys high, had an oscillation period of 26 times a minute. The oscillation of the ground was 50 a minute, and the greatest stress on the building was two-thirds of its height from the ground. Lower buildings with an oscillation period of 50 a minute moved as a whole; but still lower buildings with an oscillation quicker than that of the earthquake were broken close to the ground, for adjacent parts of a wall often moved in opposite directions.

SUITABILITY OF MATERIALS—Dewell (*Building against Earthquake Shock*, Commonwealth, San Francisco, 1st September, 1925) classifies constructions in order of resistance to earthquakes as follows: (1) the best is a structural steel frame with walls of re-enforced concrete; (2) low ferro-concrete buildings; (3) steel frame and brick walls; (4) re-enforced concrete frame and brick walls; (5) the weakest, brick buildings without structural frame.

Good ferro-concrete is so strong that the wall spaces are not distorted and the building sways like a box. A census of the damage wrought by the Tokyo Earthquake showed that of 592 ferro-concrete buildings 78 per cent. were undamaged, and only 1·3 per cent. collapsed. The movement causes the rectangular spaces in a steel framework to become rhomboids, and if the partitions are of weak material, such as lath and plaster, they are cracked and crushed in the distorted frame.

PART V

MINERAL FUELS

CHAPTER XXII

COAL AND ITS CLASSIFICATION[1]

FUELS are materials which give off sufficient heat when burnt to be of use in an ordinary fireplace, furnace, or burner. The burning of a fuel is the combination of one or more of its constituents with the oxygen of the air. Most bodies give off heat when combining with oxygen, but they are only regarded as fuel if they can be used extensively as a source of heat.

The important mineral fuels are coal, mineral oil, and peat. Other minerals serve as fuel under special conditions; pyrites is used in pyritic smelting, when both its constituents, iron and sulphur, give off heat; and oil is distilled from oil-shale. The chief fuels belong to the carbonaceous series, and depend on carbon or compounds of carbon with hydrogen. Coal is the fuel of supreme importance in the modern world. Wood and oil are its only serious rivals. Ordinary wood (e.g. ash, oak, and elm) has a calorific value of only 5420 British Thermal Units (B.T.U.)[2] while coal varies from

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[1] For coal in general, cf. E. S. Moore, *Coal*, 1922.

[2] A B.T.U. is the heat required to raise the temperature of a pound of water 1° F. (usually taken from 60° to 61° F.). A calorie is the heat required to raise a gram of water 1° C., usually taken from 14° to 15° C. To convert B.T.U. to calories multiply by $\frac{5}{9}$. Calorific value is determined by combustion in a calorimeter; but it can be estimated from the analysis by various formulæ such as that of Dulong. This formula, adapted to later determinations of the fuel values, is $8100\,C + 24{,}500\,(H - \frac{1}{8}O)\,S2250 \times \frac{9}{5}$, in which C, H, O and S are the weights of the carbon, hydrogen, oxygen, and S. Hence of a good bituminous coal with e.g. sulphur 1 per cent., hydrogen 5 per cent., carbon 74 per cent., and oxygen 7 per cent., the calorific value would be 13,468 B.T.U.

7000 to 16,000 B.T.U. Good coal is five times superior to wood when allowance is made for the difference in bulk. The large storage space required for wood renders it inconvenient in cities, while a steamship on a long voyage would require more firewood than it could carry.

DEFINITION OF COAL—Coal is not easily defined.[1] The three meanings in Johnson's Dictionary (1755), "the common fossil fewel," "the cinder of burnt wood, charcoal," and "fire; anything inflamed or ignited," illustrate the former wide meaning of the term. The coal of the Bible is charcoal, and though that term dates back to the fourteenth century, it was only restricted to carbonized wood in the seventeenth century. Mineral coal was called sea-coal, which as its use became general was abridged to coal.

Coal is a mixed mineral of very complex constitution; it is dark brown to black in colour; it consists of a mixture of carbon and hydrocarbons with earthy constituents or ash, of which the amount is not too high for use in fireplaces or furnaces; and it is insoluble in such solvents as turpentine, alcohol, chloroform, or benzine. Coal is usually defined as of vegetable origin, but the fuel value of some cannel coal is due to animal matter. Oil shales are an earthy variety of cannel coal, but are excluded from coal in ordinary usage just as sandstone containing coal fragments is classified as coaly sandstone. Cannel coal is different from other coals both in origin and use. It has been formed in lagoons and swamps by the accumulation of an organic mud which may be either animal or vegetable in origin. This mud has been called *sapropel*, and the cannel coals are conveniently separated as the *sapropelic* coals.

HUMIC COALS

The humic coals are derived from plant tissues which consist of cellulose, $C_6H_{10}O_5$, with 50 per cent. of carbon. They form a series characterized by increase in the carbon percentage, the reduction of the oxygen and hydrogen—as shown in the following table, calculated free of ash and mois-

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[1] An excellent definition—"a solid fuel which occurs in seams, being the fossilized remains of organic matter" was given by F. D. Power, *Coalfields of Australia*, 1912, p. 402.

ture—and by change into a more compact, heavier, and more brittle substance.

Humic Series	C.	H.	O.
Wood	100	12·2	83
Peat	100	9·6	55·7
Lignite	100	7·5	60
Bituminous coal	100	6·6	9·3
Steam	100	4·5	2·6
Anthracite (Pennsylvanian)	100	2·8	1·7
Sapropelic.			
Wigan Cannel	100	6·9	10·1

Peat—Peat represents the first stage in one method of coal formation. It is soft, brown or black, and varies in texture from a fibrous material in which the plants can be recognized to structureless jelly. It is an accumulation of vegetation due to the simultaneous growth and decay of plants when saturated with water, which prevents their complete decomposition into water and carbon dioxide. The plants at the upper part of the deposit decay under the action of the oxygen of the air and of bacteria and fungi; but in the lower layers, as air is excluded and the conditions are aseptic, chemical decomposition is prevented, and the materials accumulate by the continued growth of the plants above. The name probably comes from a Celtic word meaning pieces, as peat can be pulled into shreds of vegetation; it was known in England as turf until the name peat spread from Scotland late in the eighteenth century.

Peat is usually formed on cold moorlands by the growth of mosses and rushes. It is most abundant between 35° and 60° N. where the mean annual temperature is from 40° to 60° F. Its close dependence on this temperature probably explains why its formation has ceased on some Scottish moorlands, though in Ireland and Germany it grows at the rate of a foot in from 5 to 10 years. Peat is comparatively rare in warmer countries, where plant decay is usually complete; it occurs in Italy, East Africa, Madagascar, and such places as the deltas of the Ganges and Irrawadi. It is also formed in swamps and shallow pools in coastal plains, such as the Dismal Swamp of Virginia where it is forming over an area of 1000 square miles. Swamp peat may contain but little earthy material or ash, because the streams are filtered by a fringe of vegetation, and only sediment blown in by the wind reaches the middle; such peat may pass on the margin into mud.

Tropical forests produce beds of decayed vegetation, as beneath their canopy of foliage the sodden undergrowth and fallen leaves and branches form forest peat.

Peat in its raw state contains from 20 to 90 per cent. of water and usually about 80 per cent.; the amount may be reduced to about 20 per cent. by air-drying. Owing to the cost of handling and drying, peat is not an economical fuel, but being often low in sulphur, may be made into sulphur-low briquettes. It often contains from 1 to 2 per cent. of nitrogen which may be recovered as ammonia. Moderate pressure renders peat dark brown and tough like lignite; pressure alone, even of 6000 atmospheres, has but little further effect, unless accompanied by a considerable rise of temperature, when peat is made hard and brittle like coal.

LIGNITE OR BROWN COAL—Lignite or brown coal is dark brown and tough, and often shows woody fibres. It has no regular jointing, but splits into layers and weathers with curved or flat surfaces. It generally contains from 10 to 35 per cent. of moisture; a little pyrites is usually present, and the amount may be large. Lignite is light in weight (sp. gr. up to 1·3). The fixed carbon varies from 15 to 50 per cent., the volatile constituents from 25 to 50 per cent., and the nitrogen is usually about 1 per cent.; when freed of ash and moisture its heat-giving value is from 10,000 to 12,000 B.T.U. Its main defect as fuel is that it readily falls to powder; so much is lost in transport, and as unburnt powder in the smoke. Lignite is used largely as briquettes, especially in Germany, where about 4 cubic yards of lignite, which before the War cost from a shilling to six shillings to mine, make one ton of briquettes.

Brown coal deposits are sometimes of enormous thickness. A bore at Morwell in Victoria passed through 781 feet of material recorded as brown coal; and the quantity in the State is estimated as 30,000,000,000 tons; it is being worked there for use as briquettes, and the generation of electricity.

Brown coals are generally of Kainozoic age. The best-known English deposit, at Bovey Tracey in Devonshire, is Oligocene. The vast deposits in Germany and Russia are Lower Kainozoic. The lignite of Alberta, which is estimated at over 100,000,000,000 tons associated with twice as much black coal, is Cretaceous. Some Palæozoic deposits have been preserved as brown coal, such as that of Malovka, and the Papier Kohle of Toula in Russia.

Black Coal (exclusive of Cannel Coal)—Black coal ranges from a variety of lignite to anthracite, and includes three chief varieties, sub-bituminous, bituminous, and anthracite. The chief member of the series is bituminous coal. That term is a misnomer, as it was based on the view that coal contains bitumen which had been injected into a bed of earth. The insolubility of coal shows that it contains no bitumen, which can be made from it by destructive distillation.

Sub-bituminous coal or black lignite differs from brown coal by being black, harder, and having less moisture; it differs from bituminous coal by splitting into slabs instead of breaking into rectangular fragments. It contains up to about 40 per cent. of moisture. The ash is often low, but varies indefinitely; if it exceed 50 per cent. the material becomes valueless. The fuel varies in heat value from 6000 to 16,000 B.T.U. Its age is generally Lower Kainozoic or Upper Mesozoic.

Bituminous coal or ordinary house coal is black, usually laminated, and breaks along vertical joints known as cleat into rectangular or columnar pieces. The lustre varies from dull to brilliant. The coal is friable so that it soils the hands. It ignites readily and burns with a bright yellow flame. Its average specific gravity is about 1·3. The moisture is from 2 to 10 per cent. The ash in the varieties used commercially ranges from about 5 to 12 per cent. though it rises to 50 per cent., and passes into coaly clay or sandstone. The percentage of fixed carbon varies from 40 to 80 per cent; the sulphur is usually, in the varieties worked, from ½ to 2 per cent.; some seams contain 10 per cent. or more. Its calorific value varies from 10,000 to 16,000 B.T.U.

Its age is generally Upper Palæozoic, and mainly Carboniferous; but it is found in the Bathonian rocks at Brora in Northern Scotland, and in still later rocks that have undergone much disturbance. The two chief varieties of bituminous coal are the coking and non-coking. In coking coal some of the material becomes plastic and agglutinates the rest into firm cellular coke, from which the volatile constituents have been expelled as gas, pitch, coal-tar, and oil. Coke is a smokeless fuel, and is indispensable for blast furnaces as non-coking coals fall to pieces when burnt. The cause of coking has been long discussed, and is not yet fully understood. Many coals lose their coking quality on exposure to the atmosphere, and by gentle heating. The clue to this property was given by Anderson, who found that a coal which loses its coking property when heated in air retains it if heated in carbon dioxide. The loss of the property is due to the oxidation of some resinoid constituent, on the nature of which much light has been thrown by the researches of Prof. W. A. Bone (*Proc. R. Soc.*, A, 1922, c, pp. 582-98; cv, 1924, p. 625). The coking quality of coal is expressed by the "coking index," which is the proportion of sand that is cemented by a given weight of the powdered coal when heated in a crucible. Coal with a coking index of less than 11 is useless for coke; that with an index of 12-15 can be mixed with better coking coal; the grades 16-19 include good, and 19-28 the best coking coals.

Bituminous coal often consists of layers or patches of four different types of material. The dull black, often powdery charcoal-like material, known as mother-of-coal, or fusain, has been regarded as charcoal made by forest fires during the formation of the coal seam; it appears to be derived from material which has undergone carbon enrichment by decomposition before burial in the seam. Dull hard layers in coal, which are opaque in thin sections and contain many spores, consist of durain; the glossy translucent variety is clarain; and the jet-like structureless bands are vitrain.

Anthracite—Anthracite is a hard black coal which does not stain the hand, burns slowly without smoke and with a slight blue flame, and gives off intense heat. It cannot be kindled with wood; but if ignited by bituminous coal or gas it burns steadily until entirely consumed. Anthracite has a less rectangular jointing than bituminous coal, and usually breaks into nodular lumps with curved surfaces. It has usually only from 3 to 5 per cent. of volatile material, and from 93 to 95 per cent. of carbon. Its thermal efficiency is from 14,500 to 15,000 B.T.U., which is less than the best bituminous coal owing to loss of heat during its slow kindling. The intense heat generated by its combustion, and freedom from smoke render anthracite especially suitable for metallurgical and naval purposes, and slow combustion stoves.

GRAPHITE

The complete removal of the volatile constituents of coal may leave a residue of fixed carbon as coke; where the removal of the volatile matter is due to rock pressure or earth-movements the residue forms graphite, which may occur in beds, veins, or masses. Its main use, owing to its softness and permanent colour, is in "lead" pencils; fine scales are used as lubricant and polishing material. Graphite may result from the decomposition of inorganic hydrocarbons, but it is often the last stage in the coal series. The chief supplies are from Central Europe, Ceylon, Madagascar, and Korea. The price varies usually from 4d. to 8d. per lb.

SECTION II. SAPROPELIC COALS

CANNEL COAL—Cannel or candle coal is a bituminous coal, composed of sapropel, an organic mud. It varies in lustre from dull to brilliant; it may be structureless or well-bedded, and it may have a less regular jointing than humic coal. It burns with a bright yellow flame, and is sometimes so rich in volatile matter that it can be ignited by a match. Large splinters were used for lighting houses, and it thus gained its name of candle coal, of which cannel is a modification. It is often called gas coal owing to its high gas yield; its gas is too smoky to burn with incandescent mantles, and is mainly used for gas enrichment for factories where the vibration is too great for mantles. Most if not all cannel coal has been deposited in water or swamps, and it usually occurs in lenticular patches which may pass into ordinary coal or clay. In some cannel coals the volatile material is of animal origin, and may be derived largely from fossil fish.

Cannel coals are of three types—ordinary or black cannel with a ratio of carbon to hydrogen of 10 to 1, and is usually coking; brown cannel, torbanite or boghead coal, the variety richest in volatile oil-producing constituents, has a ratio of carbon to hydrogen of 10 to 1·4, contains 20 to 30 per cent. of ash and does not coke; and earthy cannel or oil shale which contains up to 80 or 85 per cent. of ash. Torbanite was the first material used on a large scale for the distillation of mineral oil, of which it yielded 120 gallons to the ton. It is named from Torbane Hill near Bathgate in Scotland, where the first large oil shale works were established. Microscopic sections show that it consists of well-bedded layers of brown coaly material, enclosing numerous yellow bodies which have been regarded as Algæ by Bertrand and Renault, and as spores by Jeffrey; some of those bodies have been formed by the re-arrangement of organic material during the consolidation of the coal, and are similar in appearance to the spherocrystals of inulin found in plants. The boghead coal of Torbane Hill contained from 60 to 66 per cent. of carbon, 8 to 9 per cent. of hydrogen, 4 to 8 per cent. of oxygen, ½ to 1½ per cent. of nitrogen, and 20 to 26 per cent. of ash.

Earthy cannel or oil shale differs from torbanite by the higher proportion of ash. It yields usually between 15 and 50 gallons of oil per ton. There is a gradual increase in ash from 20 per cent. in torbanite to 82 per cent. in the lowest worked grade of oil shale (cf. p. 294).

Classification and Origin of Coals

The arrangement of the series from wood to graphite is simple as the chemical, physical, and commercial characteristics agree; but it is difficult to express in one classification of coals the factors of practical value and the history and composition of the material. The modern classification of coals was founded in 1858 by H. D. Rogers, then Professor in the University of Glasgow (*Geology Pennsylvania*, vol. ii, pt. 2, pp. 988-95). He divided coals into five groups—anthracite, semi-anthracite, semi-bituminous, bituminous, and hydrogenous or gas coal. In the last division he included cannel, torbanite, and " asphaltic coal " or albertite, a fossil bitumen. Rogers' classification was based on the ratio of fixed carbon to volatile matter—the bituminous coals containing from 52 to 84 per cent. of fixed carbon and 12 to 48 per cent. of volatile matter, and anthracite containing 84 per cent. of fixed carbon and 7½ per cent. of volatile constituents. This system was developed by Persifor Fraser (*2nd Geol. Surv. Pennsylvania*, MM, 1879, pp. 143-4), who adopted the same divisions and based them on the ratio of fixed carbon to volatile hydrocarbons, the ratios being in anthracite 100 : 12, in semi-anthracite 100 : 67, in semi-bituminous (including dry steam coals) 100 : 62; in bituminous between 100 : 106 and 100 : 25.

Classifications based on the ratio of carbon to hydrogen have been adopted by Campbell of the United States Geological Survey; and C. H. Seyler for the coals of South Wales (*Proc. S. Wales I.E.*, 1900, xxi, p. 483; xxii, p. 112). Seyler's five divisions are based on the percentage of hydrogen—namely perbituminous with hydrogen more than 5·8 per cent., bituminous 5½ to 5·8 per cent., semi-bituminous 4½ to 5 per cent., carbonaceous 4 to 4½ per cent., and the anthracitic less than 4; each division is subdivided according to the carbon percentage. This classification well illustrates the continuity of the coal series from lignite to anthracite, but is too elaborate for general commercial use. A classification based on both physical and chemical properties has been adopted in the volumes on the *Coal Resources of the World*, issued by the International Geological Congress, 1913, i, pp. xi-xiii.

THE ORIGIN OF COAL—Coal is generally regarded as the fossilized debris of ancient forests; most coal contains so little wood that many authorities, such as Jeffreys, Lomax, Hickling and Murray Stewart, have returned to the view of Hutton in the eighteenth century, that coal was deposited as a fine-grained carbonaceous silt carried by rivers to lakes or the sea, or as a humic jelly or as sapropel, an organic mud. Another explanation—of historic interest as it was supported by Darwin and Huxley—was that coal is an injection along some permeable layer of liquid bitumen, which has incorporated the remains of plants.

Some coal has been formed *in situ* from the vegetation

	Physical Properties.	Volatile Constituents.	Carbon.	Ratio of Fixed Carbon to Volatile Matter.	B.T.U.
Anthracite	Short blue flame	3-5 %	93-95 %	Over 12—1	14,500-15,000
Semi-anthracite	Short flame; non-coking	7-12 %	90-93 %	12—7	15,000-15,500
High carbon bituminous	Short flame; non-coking	12-15 %	80-90 %	4—7	15,200-16,000
Bituminous	Luminous flame; usually cokes	12-26 %	75-90 %	1·2—7	14,000-16,000
				(Ratio of fixed carbon + ½ volatile matter to hygroscopic moisture + ½ volatile matter.)	
Low carbon	Long flame; cokes	Less than 35 %	70-80 %	2·5-3·3	12,000-14,000
Cannel	Long smoky flame; cokes	30-40 %	—	—	12,000-16,000
		Moisture			
Sub-bituminous	Streak brown or yellow fracture conchoidal	Over 6 %	60-75 %	1·8-2·5	10,000-13,000
Lignite	Streak the same; fracture earthy. Splits along bedding: fibrous structure	Over 20 %	45-65 %	—	7000-11,000

of forests or swamps. Many coal seams rest on a "seat-clay" or underclay, which is a high-grade fireclay as the constituents that act as fluxes in common clay have been extracted by plants that grew on it, when it acted as a soil. The clay often includes tree-roots (Stigmaria) which join trunks that rise through the coal seam, and around them the coal often includes fragments of fossil wood and other plant debris. The sandstone roof may contain fragments of tree-stems and leaves. Above this sandstone may occur another fireclay which is covered by coal; this recurrence may be many times repeated, the fireclay being always under the coal and containing tree-roots. The coal may be interrupted in places by bands or "horses" of sandstone; some of them join like the branches of a river, and were probably stream channels that have been filled with sand. Other coal seams, also formed *in situ*, may rest upon widespread sheets of clay without tree-roots, though the coal may contain tree-trunks; these seams grew in situations like the Dismal Swamp of Virginia or fenlands where a level sheet of clay has been covered with swamps and a growth of peat.

The theory that coal has been formed from drifted vegetation is true for other fields. Some coal seams are not underlain by fireclay, but may be interbedded with, or lie beneath it. For example, in the Kilmarnock field in Ayrshire, the seam known as the Stone Coal is divided by three layers of which two are fireclay. The Hard Seam of Ayrshire is covered by a bed of fireclay, 3 feet 6 inches thick, which rests on 4 feet 10 inches of coal, including 1 inch of shale, and the seam rests on a soft layer of coaly shale, 2 inches thick. Again in "the Patna Coal" the seam consists in descending order of—fireclay 3 feet, top coal 6 feet, sandstone 4 feet 9 inches. These fireclays moreover do not contain tree-roots, and tree-trunks in the coal may be horizontal or inverted, with the roots on the top, indicating that they drifted to their present position. Vertical tree-trunks rising from roots may occur in the Coal Measure sandstones, as well as in coal seams; thus in the fossil grove in Whiteinch Park, Glasgow, the Lepidodendron trunks are still attached to their roots; but they are in sandstone—not coal. Some coal seams which are shown by their vertical trunks and underlying fireclay to have been formed *in situ*, are of poor quality, such as the Virtuewell Seam in Lanarkshire; while the adjacent high quality coals show no evidence of growth in place. Coal seams moreover may pass laterally into shale or sandstone, or may subdivide above and below a layer of sand or clay-like beds deposited by water. The thickness of many coal seams is inconceivable for forest growths. On the estimate that 20 feet of vegetable residue are required to form 1 foot of coal, the 30-foot seam at Dudley would have required 600 feet of forest debris; some seams in India are 100 feet in thickness, and would have required a thickness of 2000 feet. The Fushun seam in Manchuria is more than 200 feet thick. Such thick deposits present no difficulty as accumulations of vegetation carried by streams from forest-clad hills into a deep lake.

The theories of the formation of coal *in situ* and by drift both appear true for different fields. In Yorkshire, and in Silesia, where twenty-seven seams are superimposed and each has its underclay, and in the South Joggins section in Nova Scotia, where repeated seams with vertical tree-trunks occur over clay with roots, the coal has been clearly formed as a forest growth; but in some fields, as in Scotland, India, and France, some seams were formed by accumulations of drifted vegetation.[1]

CARBON ENRICHMENT IN COAL SEAMS—That the main chemical change in coal formation is carbon enrichment by gradual elimination of hydrogen and oxygen is shown by the proportions of these constituents in the sequence from wood to anthracite. This process is at first bio-chemical, being controlled by living ferments in the wood and bacteria. Bertrand and Renault considered that the bio-chemical influence lasts much longer than the first stage. Coal formation has been regarded as mainly dependent on bacteria; but the particles so identified appear to be specks of inorganic matter. The biochemical processes stop at an early

[1] The view that all coal is deposited under water has been recently readvanced by Dr. Murray Stewart. He regards coal as due to bacterial action in swamps and lagoons which converts vegetable matter into particles of coal; they are washed into lakes or the sea and there deposited as a coal mud, mixed with tree-stems which he regards as also floated to their present positions, their erect position being due to the roots being weighted and therefore sinking first (*Geology of Oil Shale and Coal*, 1926, pp. 19-21).

stage and the main agents in the conversion of peat or vegetable tissue into coal are heat and pressure in the absence of air. Wood immersed in a peat bog becomes hard and black, and resembles jet. The heat of a burning coal seam converts mine timber in an open position into charcoal, but timber buried in sodden ground becomes hard, black, and brittle like coal.

Coal has been artificially prepared by E. Bergius (*J. Soc. Chem. Ind.*, xxxii, 1913, pp. 462·6) by heating peat to 584° F. in the presence of water at the pressure of 5000 atmospheres. The carbon percentage in the artificial coal depends upon the temperature and length of treatment. Coal with 84 per cent. carbon (excluding ash and moisture) required 229 hours at 590° F., but was obtained in 21 hours at 644° F. Bergius therefore calculated that peat under pressure in the presence of water at 50° F. would be converted into bituminous coal in 8 million years, and into anthracite in a still longer period. Rogers in 1858 (*Geol. Pennsylvania*, ii, pt. 2, pp. 996-7) maintained that anthracite was formed from ordinary coal by debituminization, as he termed it. De la Beche (1848) had adopted that view for South Wales, since the coals are more anthracitic in the lower part of the Coal Measures. Strahan and Pollard ("Coals of South Wales," *Mem. Geol. Surv.*, 1908) on the contrary hold that anthracite cannot have been formed from bituminous coal, as seams of both are interbedded and must have been subject to the same physical conditions. Strahan and Pollard regard anthracite and bituminous coals as formed from different kinds of vegetation.

The general evidence is however in favour of the formation of anthracite from bituminous coal. It is true that anthracite is not dependent upon igneous intrusions, which are absent from the Pennsylvanian fields, and in South Wales are older than the Coal Measures, nor upon faults which are often later than the change into anthracite. Nevertheless the deeper seams which have been under greater pressure and subject to higher temperature, generally contain less volatile matter than the upper seams; fields which have undergone especially severe dislocation yield anthracite, e.g. in Belgium, France, the Alps, and the Cretaceous coalfields of New Zealand. The fossil plants of the anthracitic and bituminous seams are the same. Of a series of neighbouring bituminous seams some may be altered to anthracite if the volatile constituents are able to escape, while other seams may remain bituminous.

The distribution of anthracite in the more deeply buried seams in especially disturbed fields, and in the older rocks supports its formation from bituminous coal. This conclusion is supported by J. Roberts who has altered bituminous coal to anthracite by heating at 900° F., and by the analytic studies of G. Hickling (*Tr. I.M.E.*, lxxii, 1927, pp. 261-76) which show the continuity of the series from peat to anthracite.

Coal Resources

Coal is not only of supreme importance as fuel, but as an indispensable chemical agent in the reduction of iron ores. The former industrial hegemony of the British Isles was largely due to cheap coal; and it has to share that position with the United States and Germany owing to their still greater coalfields. The discovery that Germany, instead of being poor in coal, had more than all the rest of Europe, was the dominating factor in European politics from 1890-1914. The output of coal is greater than that of any other mineral. In 1924 the United States had an output of 518 million metric tons, Great Britain of 271·4, and Germany of 118·8. After the three great coal-producing countries followed France with 58·8, Poland 32, and Belgium 23. The output from the United States first exceeded the British in 1899. The coalfields of the United States have an area of 335,000 square miles, while that of the British is only 12,000 square miles; hence the output per square mile of coalfield is 16 times as great in Britain as in the United States.

The vast annual output has often lead to fears as to how long this supply can be maintained. Fortunately geological research has discovered new coalfields faster than the old fields have been worked out. The world's proved coal resources are enormous. The estimates of the supplies assume that coal will not be worked at a greater depth than 4000 feet owing to the rise of temperature; but 5000 feet is certainly practicable, and is assumed as the limit on the Continent. Seams less than 1 foot in thickness are excluded as too thin;

though in some of the Scottish fields coal seams are already worked as thin as 14 inches; and some thin seam working is possible as the coal and fireclay are extracted together, the fireclay being sometimes the more valuable.

The proved coal resources of the world are 7450 milliard metric tons, of which the United States has 3840 or 52 per cent. The West Virginia coalfield had 115 milliard metric tons. Germany, excluding the fields of the Saar and of the Upper Silesia which were lost by the War, and not counting the enormous supplies of lignite, has 285 milliard metric tons, which is greater than that of any other European country. Great Britain has 189 milliard tons, Poland 170, Russia in Europe 160, France 63, Belgium 11, and the rest of Europe 29. The remaining chief coalfields of the world are in Australia; in China where the quantities are colossal but incalculable; in Canada, owing to the vast western fields of sub-bituminous coal; in India (mostly in Bengal); and South Africa.

The proved coal reserves will last for many centuries. Coal may however have a great influence in industrial redistribution. The difficulty in Britain is that the exhaustion of the more easily worked coal causes a rise in price, while railway and canal development in other countries is cheapening their production and enabling their mines to enter the world's markets. Stanley Jevons in 1865 pointed out that British industries would be hampered by a serious rise in the cost of coal, and that prediction has been fully justified. The average price of coal exported from Britain advanced from 7s. 6d. in 1850 to 13s. in 1900-1904, to 25s. 1½d. in 1923, and to 20s. 2d. in 1925. Witnesses before the Coal Commission of 1925 stated that the average pithead price of coal to the railways had increased 89 per cent. from 1913 to 1924. With the increased demand for coal and the continued exhaustion of the more easily worked British supplies, this rise in price will doubtless continue, until it has again doubled and still further handicapped industries. Other sources of energy are available, and will be more employed as coal rises in price. Water-power is used in some countries where there are convenient waterfalls and high level lakes, and coal is dear; but water is usually an expensive source of power, while harnessing the tides, owing to the huge works necessary, is still economically impracticable. Wind may be used for pumping and for small sources of power, but it is too uncertain for many industrial purposes. Subterranean heat is being tapped in areas of volcanic activity, and solar heat in dry tropical countries; but these sources are handicapped by the fact that they cannot be utilized on a large scale except near great markets, with cheap supplies of ores, fluxes, and other raw materials. There is no apparent alternative to coal as the source of power for the primary industries, except in limited areas.

CHAPTER XXIII

MINERAL OIL[1]

Petroleum — History and Nature — Petroleum is the second in importance of mineral fuels. The name is mediæval, and means rock oil, for, as remarked in 1543 petroleum "droppeth out of rocks." Many places, such as Pitchford in Derbyshire, and Pechelbronn (i.e. Pitchspring) in Alsace, are named after oil springs. Petroleum, however, dropped out of the rocks in North-western Europe in such small quantities that it was only used as medicine or cart grease. In other countries it was used in early times, as by the Peruvians for embalming mummies, by Noah to caulk his ark, and as the mortar for the Tower of Babel. Later in the Bible it is mentioned as used in paving, for the parable of the salt that has lost its savour, and is fit only to be cast out and trodden under the foot of man, probably refers to petroleum which has lost its volatile constituents, and is useful for road making. Crude petroleum is usually a dark brown to greenish-brown fluid, though it occasionally undergoes natural filtration and is almost water-clear as in some Canadian and Trinidad wells. It is a hydrocarbon of extremely varied composition. In the methane or paraffin series each molecule of carbon is combined with the maximum quantity of four molecules of hydrogen, so that the carbon is fully saturated. The paraffin series is represented by the formula C_nH_{2n+2}, e.g. CH_4. Other groups are marked by lesser proportions of hydrogen, so that the compounds are usually unsaturated. The chief series are the ethylene or olefine, C_nH_{2n} (e.g. C_2H_4); acetylene, C_nH_{2n-2} (e.g. C_2H_2);

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[1] The U.S. gallon holds 8·33 lb. of water, the Imperial gallon holds 10 lb.; the barrel contains 42 U.S. gallons and 35 Imperial gallons; the metric ton is 6·295 barrels, 2204 lb. or 1000 kilograms.

the camphenes, C_nH_{2n-4} (e.g. C_3H_2); the benzenes,[1] C_nH_{2n-6} (e.g. C_6H_6), and the naphthenes, $C_nH_{2n-6} + H_6$ (e.g. C_3H_6, C_4H_8). The series include many hundreds of different compounds.

Physical Classification—Petroleum is divided into four groups on physical properties. The first group includes marsh gas and natural gas, which are gases at ordinary temperatures, and the volatile oils which evaporate below 300° F. such as the petrol ethers, e.g. cymogene that vaporises at 82° F., and the petrol spirits, such as petrol or gasolene as it is known in America. Naphtha and benzine are grades of petrol. The second group includes the lighting oils, e.g. kerosene, which distil at temperatures of from 300° F. to 570° F. The third group consists of the heavy lubricating oils which are not inflammable and distil at above 570° F. The fourth group includes the solid petroleums, such as paraffin wax, ozokerite, and such bitumens as albertite, grahamite, elaterite, etc.

Baumé Scale—Specific gravity gives useful guidance as to the nature of a crude oil. The light oils contain more petrol than those of a higher specific gravity. Oils are usually compared by the Baumé scale, which states the degree to which an hydrometer (graduated from 10 to 100) will sink in the oil. The specific gravity of water is marked on the scale as 10. The lighter the oil the deeper the hydrometer sinks, so that the Baumé degree is higher. Thus 20° B marks a specific gravity of ·9333, and 30° B. of ·875. This scale directly indicates the weight of the oil; for a fluid of 10° B. weighs 10 lb. to the gallon; one of 20° B., sp. gr. ·933, weighs 9·33 pounds to the gallon; one of 30° B., sp. gr. ·875, weighs 8·75 lb. to the gallon, and so on. This convenient relation does not apply to the American gallon, which weighs 8·33 lb. instead of 10 lb. to the gallon.

Supply of Oil—In the search for oil geological guidance is now generally recognized as indispensable. J. E. Pogue in his *Economics of Petroleum* (1921, p. 343), reports that according to the records of a great American oil company, 85 per cent. of the wells sunk on geological advice had been

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[1] Benzene, C_6H_6 must be distinguished from benzine, a grade of petrol.

productive, while of these sunk without that advice only 5 per cent. had been productive. Seventeen wells sunk in accordance with geological advice were successful for one sunk at random! The unproductive expenditure in the search for oil is shown by the statement in the Queensland *Government Mining Journal* (xxvii, March, 1926, p. 85) from "a competent authority," that in the United States 12 billion dollars have been spent in the search for flow oil, exceeding by four billion dollars the total value of the oil recovered.

Although the supply of oil is not assured the temptation to use it regardless of the future is strong because it is such an ideal fuel, being clean, easy of transport, and economical of labour. Light oils are at present indispensable for motor engines, and oil has no rival in lighting isolated houses. Its use for shipping has such advantages that while in 1914 the tonnage of oil-using steamers was 1,310,000 tons, the tonnage had increased by 1924 to 17,154,000. In January 1925, of the shipping then under construction, 60 per cent. were designed for oil engines. The increase of motor traffic leads to increasing demands on the light oils; in 1925 there were 19,954,347 registered motor cars in the United States, and the output of motors in that country in 1926 was 4½ millions. The number of motor cars in Britain in 1926 was almost 2 million.

With these increasing demands warnings have been often made that the oil supply of the world would be early exhausted. The highest authorities have repeatedly stated that the United States output was at its maximum, and that a serious decline must begin. Nevertheless, to the confusion of the prophets its output in 1926 was its highest, and it provides 70 per cent. of the world's supply. Similar predictions have been even more positive in regard to natural gas. Pogue in 1921 claimed that the maximum had been passed, and yet the output had increased 60 per cent. by 1924, and has continued to rise slightly. The predictions do not suggest any absolute exhaustion of petroleum because a higher percentage from the oil beds could be won; but these methods involve such increased cost that oil would become too expensive for many uses. In 1917 the rise in oil prices owing to the War led to an orgy of well-drilling in America, and at the advice of the Geological Survey special efforts were made to reach the untouched deep level oil beds in California; and wells have now been sunk there to depths of over 8300 feet. The increased yield made California the most prolific of the States, and led to a serious fall in the price of crude oil. California reached its maximum of nearly 263 million barrels in 1923; but its decline has been more than counterbalanced by increased yields from Oklahoma and Texas. Nevertheless, in September, 1926, the Federal Oil Conservation Board of the United States (*Report*, pt. i, 1926, p. 6; and cf. p. 8) states that the oil available by flowing and pumping wells from the present producing and proven fields would only maintain the present output for six years, and that of the current production more than half comes from only 4 per cent. of the wells, which are for the most part only a year or so old, and from fields that have been discovered within the past five years. The life of the fields, it proclaims a matter of grave concern.

THE ORIGIN OF OIL—Success in search for petroleum is helped by a right conclusion as to its origin. Chemists have repeatedly asserted that mineral oil is an inorganic product, due to the action of superheated steam on iron carbides in the interior of the earth. This theory is a chemical possibility, but is disproved by the evidence of distribution. If the oil came from the interior it should be found mostly in old rocks and be rare in new rocks. The reverse is the case. Oil is not found in any commercial quantity in the most ancient rocks of the earth's crust nor in the Cambrian. According to Beeby Thompson (*Oil-Field Explor.*, i, 1925, p. 16), out of a total production to the end of 1923 of 12,094,000,000 barrels, the Kainozoic yield was 44 per cent., the Mesozoic 15 per cent., and the Palæozoic 41 per cent. Of the Palæozoic 88 per cent. is Permian and Carboniferous, 2 per cent. Devonian, and 10 per cent. Silurian and Ordovician. Hence the youngest geological Group yields most oil, and in the Palæozoic the upper Systems are the most productive, and there is practically none in the lowest, the Cambrian.

Petroleum is an organic product due to the slow distillation of buried animal and vegetable tissues by heat and pressure. The organic nature of oil is suggested by its composition of carbon, hydrogen, and oxygen, which are the chief constituents of ordinary animals and plants. True oil shale contains no oil, but organic residues which, when heated in a retort, are converted into oil. According to the organic theory mineral oil is similarly produced from the organic matter in sedimentary deposits. Oil comes from beds charged with organic material and is only found in igneous rocks which have been injected with it from sedimentary rocks. Pockets and trickles of petroleum are frequently met with in the igneous rocks of the Scottish oil-shale field, but only where the oil may have been distilled out of shales; the field of Bacuranao in Cuba is fed from an serpentine, which has doubtless been impregnated from sediments.

That the mineral oil was not formed synthetically is shown by its optical properties. Synthetic oil does not cause circular polarization, but mineral oil does. Its circular polarization is sometimes attributed to the presence of some organic oil—cholesterol ($C_{25}H_{26}O$), which is familiar as lanoline and is an animal product, or phytosterol, a corresponding oil derived from plants. According to this improbable suggestion mineral oil is partly inorganic and partly organic.

Most authorities agree that mineral oil is of organic origin, but there is wide difference of opinion as to whether it is mainly vegetable or animal. Its frequent association with coal and lake deposits is advanced in support of its vegetable origin; but large quantities come from Silurian and Ordovician rocks that are earlier than any land vegetation that would have produced spores and seeds. Animal tissues can be distilled into oil similar to petroleum, and most of the organic matter in many oil-producing beds is more likely to be animal than vegetable. The Scottish oil shales contain abundant fossil fish and entomostraca, and many fields obtain their oil from shales rich in foraminifera and other animals. The constant association of fish with oil deposits has indeed led J. H. Macfarlane to claim in a volume entitled *Fishes, the Source of Petroleum* (1923, p. 414), not only that petroleum is wholly of animal origin, but that fish alone are its source. Petroleum is probably derived from both plants and animals, and animals appear to contribute the larger share.

The quick accumulation of thick masses of sediment rich in organic material is most likely to lead to a prolific oilfield. Accordingly those great subsiding areas known as geosynclinals are the seat of the chief oilfields. The tropical and subtropical countries are more favourable than polar regions, where organic matter is less abundant.

INDICATIONS OF OIL—The existence of subterranean oil is indicated by several features :—

(1) The most obvious are seepages of gas and oil. Gas may escape unseen unless discharged under water; it may supply perpetual gas springs, such as those at Baku which have been burning for thousands of years in the temples of the Fire Worshippers.

(2) Escaping oil often forms iridescent films on pools and if set on fire forms a "burning pool." Oil films may be distinguished from those of oxide of iron or manganese by their odour, and by stirring with a stick when a metallic film breaks into pieces, and an oil film reunites into a single patch. A film of oil may be a clue to a large deep-seated supply which constantly renews the film as it evaporates; but it may result, as in some deltas from the decay of recent organic matter.

(3) A petroliferous sandstone may indicate an underground oil supply; the rock at the outcrop may give no sign of oil, but freshly broken surfaces have a fetid odour, remarked in the name stinkstone. If petroleum or bitumen occur in a rock and a sample be crushed in chloroform its evaporation in a dish leaves a black rim. A bituminous sandstone may act as an impermeable cap and imprison oil in beds below. The Brea of California consists of pitch which has plugged up the outlets from underlying beds, in which the oil has accumulated; the oil is reached by boring. A bituminous sandstone may however indicate that the oil has evaporated and left only a solid residue. The most famous petroliferous residues are the pitch lakes of Trinidad and Venezuela which have been left by the evaporation of large quantities of oil. Bitumen also occurs in veins and "dykes," such as the albertite veins of New Brunswick, along channels by which oil reached the surface. Limestones often contain bitumen disseminated through the rock or collected in simple or branching gash veins. The bitumen may be the residue of the soft tissues of the organisms that formed the limestone.

The rock material having accumulated quickly, the organic matter was deposited with the shells and has been distilled into bitumen, which having no escape, collected in cracks or pores in the limestone. Gash veins of bitumen in limestone may therefore indicate no large supplies of oil, and boring for oil beneath a limestone in which the oil is indigenous is naturally unsuccessful. Where, however, the limestones have been impregnated from below their bituminous veins may be a clue to underlying oil supplies.

(4) Some mud volcanoes are due to the escape of petroleum vapours, which carry up with them hot mud, and pile it around the vent, as in the mud volcanoes of Burma, Trinidad, and the coast of Beluchistan. In the Baku oilfield mud hills thus formed are 1300 feet high. Carbon dioxide or sulphuretted hydrogen denotes a volcanic origin; but a gas of the petroleum series indicates that the "mound spring" is not volcanic and that petroleum may occur underground.

(5) Burnt clay is sometimes due to the burning of petroleum, as in Barbados; but it may be a result of contact alteration. If the clay has been completely fused into a black glass (pseudotachylyte), the high temperature necessary for this change may be due to the burning of producer gas generated by the action of steam upon a hot hydrocarbon.

(6) Salt is such a frequent associate of oil that the two are often regarded as connected in origin. In England, and elsewhere, thick beds of salt are found without oil, but in some fields, as Ohio and Rumania, salt and oil are so intimately connected that the salt is believed to have helped in the formation of the oil.

(7) The presence of sulphur is often also regarded as an indication of oil, but the association may be a coincidence.

(8) The most likely part of a coalfield to yield oil has been deduced by D. White (*Journ. Wash. Acad. Sci.*, v, 1915, pp. 189-212) for the Appalachian area and Mississippi valley, from the isovols, or lines drawn through places where the coal has the same ratio of fixed to volatile carbon. In an anthracite field the isovols may be above 90; some fields with isovols above 70 contain neither gas nor oil; a little of both may occur between isovols of 65-70; and oil in commercial quantities is found where the isovols are below 65. This method is not of universal application as some coalfields

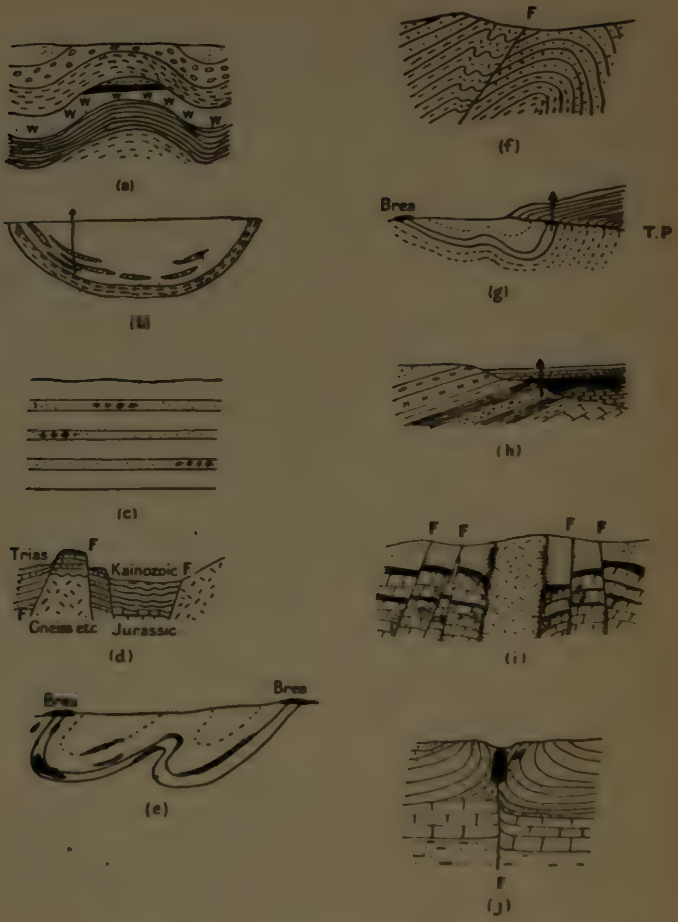

FIG. 63.—A-J. COMPARATIVE OILFIELD SECTIONS.

(a) An anticlinal structure with the oil (solid black), floating on the water in the water-bearing oil bed, W, and enclosing above it the natural gas (dotted).

(b) An oil well in a synclinal draining lenticles of sand as at the Florence Field, Colorado.

[*Description continued on opposite page.*

with suitable isovols are barren of oil. It is only applicable where the general distribution of the coals is well known, so that allowance can be made for those with an especially high proportion of volatile matter. Moreover, in the absence of porous beds in which oil can accumulate or of suitable structural conditions a high ratio of volatile to fixed carbon may occur without supplies of oil.

ESSENTIALS OF OILFIELDS AND OILFIELD STRUCTURES—The geological conditions essential to a great oilfield are first the presence of sedimentary rocks, with or without igneous rocks. Second, the presence of beds, such as sand, sandstone, or jointed limestone, which contain sufficient pores or other spaces to hold a considerable supply of oil. Third, the absence of extensive metamorphism later than the date of the possible oil-producing bed. Fourth, local material rich in organic matter. Fifth, an impermeable cover to prevent the oil escaping at the surface. Sixth, water conditions favourable to the concentration of oil into pools.

(c) Oil pools in horizontal beds of sandstone. The oil is concentrated by the surface tension of the water. The fact that in the successive oil-bearing beds the pools are not superposed shows that the oil concentration was not due to an undetected anticlinal.

(d) The oilfield in the rift-valley of the Upper Rhine. The oil occurs in Kainozoic beds which have been slightly folded by compression between faults (F) which bound the Vosges to the W. and the old rocks of the Black Forest to the E.

(e) Oil distribution in isoclinally folded beds in California. The underground oil pools are shown in black. The outcrops are plugged by patches of Brea.

(f) Oil pools in beds due to over-folds and overthrust faults as in Galicia. The beds with dots are Oligocene and those with bars are Eocene.

(g) Oil pool formed beneath a thrust-plane, TP., which has thrust impermeable beds over the end of an oil-bearing layer; the outcrop is sealed by a patch of Brea.

(h) An oil pool due to an unconformity. The oil-bearing bed is capped by a bed of shale in the upper series.

(i) Oil accumulations due to igneous concentration as in Mexico. An igneous block in the centre has invaded a series of Cretaceous limestone and Eocene shales. The distillation of the organic matter of the limestone has formed pools of oil shown by the black bars along the faults (F) and in permeable patches of the limestone.

(j) An oilfield formed at a salt dome. The salt dome, has formed by salt solutions rising from the basal red sandstones with salt patches, up the fault, F. The ascent of the salt plug has contorted the overlying clays.

Seventh, suitable geological structures for the beds to act as oil reservoirs.

Large areas of the earth can be dismissed as unlikely to yield oil, such as great massifs of plutonic rocks and areas of regional metamorphism and volcanic fields, unless they contain unaltered sedimentary rocks.

Oil is found with different geological structures (Fig. 63, *a-j*). The first favourable position discovered was along an anticline. The early oil wells in Pennsylvania were sunk at random; certain lines were productive and were called "directive lines." In 1859 Sterry Hunt recognized that they lay along the crests of anticlinals. He concluded (*Canad. Nat.*, vi, 1861, pp. 242, 250-1) that the oil had been concentrated along these upfolds, and he remarked "we may reasonably expect to find others (i.e. good wells) along the line of the anticlinal or of the folds which are subordinate to it." This view had been previously suggested for Burma by Oldham (1855, *Mission Ava*, p. 309). The anticlinal position is favourable in water-logged beds as the oil floats on the water and collects beneath an impermeable arch. Any natural gas present will collect at the top of the arch above the oil. If a bore pierces the impermeable beds of such an anticline the gas escapes first, the oil next, and water last (Fig. 63 *a*).

Anticlines are especially favourable reservoirs because the oil beds are there nearest the surface and the oil is automatically discharged by the underlying water. Hence wells in anticlines are so convenient and economical that they are naturally sought for, and prospecting for oil has been described as simply prospecting for anticlines. A dome is even more advantageous, for the oil is compressed into a pool at its top.

Nevertheless, the widespread expectation of "no anticlinal no oil" is not justified. Oil is often absent from anticlines and found in synclines. In dry rocks owing to the absence of water-pressure, unless local heat raises gas-pressure, the oil works downward and collects in the trough or syncline. Even where anticlines are productive oil is often found along the synclines. In other fields, as in the Argentine and Colorado, the oil is dominantly synclinal. Oil is also largely found in beds with a uniform or homoclinal dip (cf. Fig. 63, *h*), which is also described by the hybrid term of uniclinal. Many of the chief oilfields are in homoclinal and not anticlinal areas. The oil may rise along a porous bed in the homoclinal series and collect where the bed is blocked by a fault or dyke, or becomes thinner or denser, or has been plugged by bituminous matter.

Oil also occurs in horizontal beds. It has been claimed that the oil really occurs along anticlines which are so gentle that they are not recognizable; but if the beds were anticlinal, the pools in the successive beds should occur one below another, like the saddle-lodes of a goldfield; but the pools at different levels may not be superposed (Fig. 63, *c*). The pools may be due to lenticles or patches of porous sand in clays, or the concentration of the oil by surface tension. If a mixture of oil and water soaked into a bed of irregularly mixed sand and clay, the surface tension would force the oil into the sandier patches, leaving the water in the clays. Many oil pools in horizontal and inclined beds are doubtless due to this process.

Oil may also occur in thin seams or gash veins in limestone, due to the gradual production of bitumen from the organic matter of the rock, and its collection in shrinkage cracks. Large accumulations of oil also form where fractured limestones are capped by an impermeable bed, as in Mexico; but in these cases as there may be no evidence on the surface as to the distribution of the fissures, boring is very uncertain. Though oil is not formed in igneous rocks it may be forced into them by gas-pressure when distilled from adjacent rocks by heat. Colossal oil pools occur in Mexico beside intrusive igneous rocks (Fig. 63, *i*).

ESTIMATION OF OIL RESOURCES—The estimation of the reserves of oil in a field is more difficult than that of coal or ore. It is rarely possible for a surveyor to enter the oil bed, while an adequate number of bores to test the reserves might be too costly and even dangerous. Of the two chief methods of estimating oil reserves, the first is determination of the capacity of the oil sands, i.e. their area multiplied by their thickness and by the amount of pore space. The result shows the maximum amount of oil that would be present if the whole bed were saturated with oil. This "saturation method" is deceptive because the pores may be partly empty, and only an uncertain percentage of the oil is recoverable. It is generally considered that under present conditions only from 10 to 20 per cent. of the oil in a bed is obtained, and that most fields, except under heavy water-pressure, do not yield more than 10 per cent. The life of a field can therefore be prolonged by an improvement in the recovery factor, either by more vigorous pumping, by the explosion of a torpedo at the bottom of a well to open up the fissures and to secure the better drainage of the adjacent beds, or by the increase of gas-pressure either by raising the temperature or by forcing down compressed air.

The second, and more reliable method of estimating the oil reserves of a field is by the decline in yield of the wells. (Cf. Tables by C. H. Beal, *U.S. Bur. Mines*, *Bull.* 177, 1919). The output of a well is usually greatest when it is first opened; the fall in yield is rapid during the first few weeks; and the quick fall during the first year passes into a gradual decline. In the Oklahoma field, e.g. if the yield of a well in the first year is taken as 1, in the second year it would be from ·25 to ·75, and the total yield would be 2 or 3. In California if the yield of a well in the first year is 1, in the second year it is ·75, and the total is 5. For most fields a diagram can be prepared showing that as the well approaches exhaustion the decline is very slow, so that after the large yield a small supply can be obtained for years by pumping at appropriate intervals, say for an hour a day or at intervals of a week. The future supply from a field can be estimated from its "decline curves."

The different oilfields of the world are under such different conditions that a geographical summary is more useful than a systematic classification.

The Oilfields of the United States—The oilfields of the United States had yielded by June, 1926, over 9000 million barrels of oil, and they contribute about 70 per cent. of the world's supply.

The eastern or Appalachian fields were the first discovered. Petroleum had long been known there to the Indians and a little was found in Pennsylvania while boring for brine between 1790 and 1820. The modern development of the American oil industry dates from 23rd August, 1859, when

Drake struck oil at Titusville beside Oil Creek in Pennsylvania. It was the first of the 680,000 wells that have been drilled for oil in the United States up to 1926, and it led to the opening of the great field which extends west of the Appalachian Mountains through Pennsylvania, Ohio, Indiana, and Illinois. The rocks range from the Ordovician to the Carboniferous. Ordovician rocks are raised to the surface in the W. by the broad Cincinatti anticline, and the Lima-Indiana field obtains oil from depths down to 1000 feet from the Trenton Limestone which underlies the Hudson River shales. The Silurian beds outcrop further E. and the central Ohio field is fed from the Clinton Sandstone and Niagara Limestone. These porous beds are capped by the Devonian Ohio Shale. Further E., in the geological centre of the field, the synclinal of West Virginia and Pennsylvania consists of Carboniferous rocks; pools of oil occur along many secondary folds, especially the anticlines; but some were along synclines while the adjacent anticlines were barren (e.g. the Whiteley and Waynesburg synclines, Stone, *U.S.G.S.*, *Bull.* 225, 1904, pp. 409-10, and the Hinton Syncline, Kentucky, *ibid.*, 688, 1919, p. 69).

The mid-Continental field, in Oklahoma, Kansas, and Texas, includes rocks ranging from the Carboniferous to the Cretaceous. The oil appears to have originated from the Carboniferous and some has accumulated in Permian sandstones. The oil is sometimes found in domes; but most comes from homoclinal beds; some of the pools are in almost horizontal beds, and occur in patches of porous rock surrounded by shale (Taff and Shaler, *U.S.G.S.*, *Bull.* 260, 1905, pp. 441-5). The Oklahoma field has been the greatest producing field in the United States until for a time surpassed by California.

Northern Texas is the continuation of the Oklahoma field. In Southern Texas the oil is found associated with salt domes, of which 62 were known by 1922; others have since been found by earth-waves due to explosions and by the torsion balance. The distribution of the oil in these domes is apparently capricious, and a high proportion of the wells has proved barren. The formation of salt domes is considered, page 213. They have probably been impregnated with oil from the shales through which the salt block has arisen. The most famous of these salt domes is Spindletop from which, after nine years unsuccessful drilling, the Lucas "gusher" in January, 1901, discharged 700,000 barrels of oil before it could be controlled; it yielded 17 million barrels in 1902; it is also historically important as it provided the clue to the Mexican oilfields.

The Rocky Mountain oilfields extend from Montana through Wyoming into Colorado. The rocks range from the Cambrian to the Cretaceous or occasionally Eocene, and have been bent into broad folds. Oil is sometimes found in an anticline, as in the Labarge field in Wyoming, although it contains no water and the oil is therefore not forced upward by water-pressure (cf. Schultz, *U.S.G.S.*, *Bull.* 340, 1908, p. 369). In some of the fields, as in the Cretaceous of Montana, the oil is found on the margins of synclinals. The Colorado fields are also in the main synclinal. The Florence oilfield (cf. Fig. 64, *b*), which by 1892 had yielded 95 per cent. of the Colorado oil, was discovered in the search for water. It is in a great elliptical syncline of Jurassic and Cretaceous rocks, the centre of which must be 8000 feet deep. A little oil comes from the Jurassic, but the bulk is from the Cretaceous Pierre clays. The deepest well is 3650 feet, and the oil does not appear to occur lower as the slope below is too gentle to maintain the flow of the oil; it collects at the foot of the steeper part of the syncline, in sandstone lenticles, which are separate as wells even 25 feet apart are fed independently. The oil is obtained by pumping and wells paid with the yield of about 7 to 8 barrels a day. The Rangeley field, also in Colorado, occurs in Jurassic or Cretaceous beds in an anticline and the wells occur in pockets in the Mancos Shale, Cretaceous (H. S. Gale, *U.S.G.S.*, *Bull.* 350, 1908, pp. 44-6).

California has made a sensational but anticipated addition to the American oil supply, the output being raised to 263 million barrels in 1923. Wells have been sunk to the depths of over 8300 feet. The Kainozoic rocks range from Eocene to Pleistocene, and are 34,000 feet in thickness, of which 20,000 feet are Miocene; their oil is derived from the distillation of the soft tissues of foraminifera, diatoms, etc. Some of the oil comes from the underlying Cretaceous beds. The structures of the Californian fields differ greatly. The central field near Coalinga yields oil from lenticles of sandstones and shale in gentle dipping homoclinal beds. In the Central field, as at McKittrick, the beds have been intensely contorted and overfolded ; the oil beds reach the surface, but the escape of the oil from some of them has been stopped by deposits of pitch or brea which have plugged the pores (cf. Fig. 63, *e*). In part of the Los Angelos field, the large yields from which in 1923-4 disturbed the oil markets of the world, the oil came from deeply buried domes of thick Miocene sand. Most of the Californian oil has an asphaltic base and is of moderately high density (14°-15° B.) ; but the deep oil is lighter and has probably been derived from the diatom beds of the Lower Miocene. In the Summerland field the wells are sunk from piers built from the shore ; the oil comes from shales beneath the sea and percolates into a fault which there bounds the coast.

Mexico—The Mexican fields are an extension of those of the South Texas. The ordinary Mexican oil has an asphaltic base, is thick and heavy, with a grade of 11°-12½° B., contains much sulphur, and in use is usually mixed with lighter oils. The chief fields lie to the west of the Gulf of Mexico near Tampico and along the Tuxpan River, and they have yielded the most violent gushing wells yet encountered.

The rocks of these fields range from the Cretaceous to the Pliocene. They have been folded and fractured by repeated movements, and traversed by many dykes and masses of basalt and dacite (cf. Fig. 63, *i*). The chief oil-yielding bed is a thick cavernous limestone, the Tamasopo Limestone of Middle Cretaceous age, which has been fractured and oil distilled from it by igneous intrusions. The oil has risen from this limestone into the Upper Cretaceous San Filipe beds, a sheet of thin limestones and shales. These beds are a good oil reservoir as they are capped by 3000 feet of the Mendez Shales, which are Upper Cretaceous to Eocene. Owing to the thick shale cap the oil collects in the San Filipe beds and on the margin of the basalt dykes, where it is under such heavy gas pressure that when tapped by a well the oil may discharge with uncontrollable violence ; after a gusher has flowed for a few months the supply may suddenly cease and be replaced by salt water. The gas pressure of the Dos Bocas well in 1908 led to its eruption with such violence that the whole of its hundred million barrels of oil was lost.

Many Mexican wells yielded up to 60,000 barrels a day, but the life of such wells is short. Heavy losses were incurred by these uncontrollable flows catching fire. The "Potero del Llano, No. 4," 1914, which discharged an accumulation of oil beside a basalt intrusion into Cretaceous limestones, is one of those famous for the disasters due to its superabundant oil.

The Isthmus or Tebasco fields on the Tehuantepec Isthmus were opened in 1905. The wells are associated with salt domes and are of the South Texas type; in the eastern part of the field the wells are associated with an anticline. The wells in the Isthmus fields have been less productive than the main group, but some of the oil is lighter and of better quality.

Canada—The oldest of the three chief Canadian oilfields is in the Ordovician limestones of Southern Ontario, and is an extension of the Appalachian field. The productive rocks range from the Ordovician to the Devonian and the oil comes from limestones; the chief pools were in the Devonian Onondaga Limestone; smaller contributions come from the Silurian beds and the Ordovician Trenton Limestone. The Alberta field at the eastern foot of the Rocky Mountains is an extension of the Rocky Mountain field of Montana; but that line does not promise to extend far into Canada owing to the huge intrusions of granite. N.W. of Edmonton are the Cretaceous Athabasca tar-sands, of which the bitumen may be the heavy residue left by the evaporation of crude petroleum. The quantity of this bitumen is immense.

Where the Arctic circle crosses the Mackenzie River to the W.N.W. of Fort Norman is an anticline of an Ordovician coral limestone, 6000 feet in thickness, and near it seepages of petroleum have long been known. Borings from 1914-21 proved the existence of oil, but the development of the field is hampered by its remoteness. This oilfield and one further north in Northern Alaska are the two farthest from the Equator.

West Indies—The West Indian Islands include four oilfields. The most famous is Trinidad, to which attention was directed by the Pitch Lake (137 acres; 135 feet thick; Cadman, *Tr. I. Min. Eng.*, xxxv, pp. 453-80), which is regarded as a residual deposit left by the evaporation of 40 million tons of petroleum (Thompson, *ibid.*, xxxv, p. 478).

Trinidad has yielded many wells chiefly from the Lower Kainozoic rocks which have been intensely folded and disturbed. The folds run E. and W., continuing those of the Cordillera of Venezuela into the Atlantic. Some of the Trinidad oil is high-grade and can be at once used as petrol; it was doubtless naturally refined from crude petroleum and has migrated into beds of sand. The foundation of Barbados consists of deltaic deposits of Lower Kainozoic age covered by deep-sea deposits and coral reefs. The foundation beds yield manjak or Barbados tar, and bores have obtained some petroleum.

Cuba consists of Jurassic to Oligocene limestones which rest on a basal serpentine; the rocks have been folded and fractured, and oil distilled from the limestone has travelled through the porous rocks, depositing in some places seams of asphalte and in some places impregnating the sand with colourless petrol (sp. gr. ·72; 62°-65° B.), and at Bacuranao near Havana, impregnating the serpentine with a heavy oil (sp. gr. ·88; 28° B.).

South America—The extensive pitch lakes in Eastern Venezuela have long encouraged hopes of the existence there of important oilfields. Prolific fields have been found in Western Venezuela near the Gulf of Maracaibo. The rocks of Venezuela include a folded foundation of pre-Palæozoic metamorphic rocks, on which rest 5000 feet of Cretaceous limestones and dolomites, 7000 feet of Eocene to Oligocene shales with coal and oil, and 5000 feet of Pliocene sandstone, gravels, and shales. The whole series has been folded by post-Miocene movements, which in Eastern Venezuela trend E. and W. parallel to the main West Indian trend; but in Western Venezuela they bend round to the S.W. and S., and pass into the Andes. The general sequence offers many resemblances to that in Mexico; but the oilfields have not been affected by volcanic action and igneous intrusions, and the gushing wells are more easily controlled. Some of the oil may be derived from Cretaceous limestone, but apparently most of it has come from the Oligocene shales and has been stored in the Miocene beds. The oil is usually heavy (about sp. gr. ·93 and 21° B.).

The oilfields of Peru occur in Kainozoic beds at least 17,000 feet thick (Negritos, Eocene, 7000 feet; Lobitos, Oligocene, 5000 feet; and Zorritos, Miocene, 5000 feet). These beds have been disturbed by a great fault parallel to the coast, and from it branches run inland and break the country into large fault blocks. The oil is found in evenly dipping beds, and not in anticlines, and the beds are mostly waterless. The oil seems to have been distilled from organic matter by the heat due to the earth movements; but the connection is not obvious as the oil is not found in direct relation to the faults.

In the Argentine some promising anticlinal lines proved disappointing; but bores for water in the basin of the Lower Chuput River near Comodoro Rivadavia reached heavy fuel oil in Cretaceous shales. This field as a whole is a great syncline, with oil pools in secondary anticlines on its floor.

EUROPE—In Europe and Asia the chief oilfields occur along the Alpine-Himalayan mountain system. Most of the oil comes from Kainozoic marine shales containing abundant foraminifera or marine diatoms or algæ, or from bituminous limestones. The oil has been derived by the distillation of the organic matter by the heat and pressure of earth movements. The geological structure of some fields is very complex.

The westernmost field is in the rift-valley of the Upper Rhine, where Oligocene sands have been dropped between the faults and crumpled (Fig. 63, *d*). The oil from Pechelbronn was known in the fifteenth century, and has been obtained since 1735 by dug wells; deeper beds with lighter oils were found by boring, and are now being mined, as 70 per cent. of the oil can be recovered fron the sands by drainage into galleries, whereas only 16 per cent. was obtained by wells (de Chambrier, 1921).

In Poland the oil industry dates fron 1853; drilling began in 1870, and the field reached its maximum yield of 15 million barrels in 1899. The productive rocks range from the Cretaceous to Miocene, the Eocene being the richest; the beds have been elaborately overthrusted and overfolded (cf. Fig. 63, *f*), leading to local accumulations of oil. In Roumania the rocks are also intensely folded and faulted by the Alpine movements; the oil beds range from the Cretaceous to the Pliocene and they contain much gypsum and salt; the oil has collected into some rich pools; thus 130 acres at Moreni has yielded over 52,500 barrels per acre. Some Roumanian upfolds have been broken through by rising cores of rock and salt-domes (Fig. 55).

ASIA—CAUCASUS, PERSIA, BURMA, EASTERN ARCHIPELAGO —The Baku field, W. of the Caspian and S. of the Caucasus, has yielded oil and natural gas throughout historic times. The oil comes from Pliocene, Miocene, and Oligocene sands which occur as lenticles in clay. The beds have been folded and the main supplies, as from Bibi Eibat, are from anticlines. Some wells must draw their oil from a large area, for one plot of 27 acres in that field has yielded in 36 years 2,200,000 barrels of oil per acre, or sufficient to cover the ground to a depth of 286 feet (Beeby Thompson, *Oil Field Exploration*, i, 1925, p. 335). The surface is largely occupied by barren freshwater sands, which overlie the Lower Pliocene oil sands; they rest upon the Spirialis beds from the abundant organic matter in which the oil may be derived. In the Caucasus other oil supplies came from Miocene and Oligocene beds, which include lacustrine and marine shales rich in diatoms, fish, and mollusca. The Baku field has hitherto been the most prolific oilfield in the Old World.

The Persian and Mesopotamian oilfield lies along the fold-mountains of the Persian Arc, which runs from near the Caspian through South-western and Southern Persia till it rejoins the axis of the Alpine-Himalayan System in North-western India. The Cretaceous rocks include many gash veins, and according to one hypothesis the oil has risen from the Mesozoic limestones into the porous beds of the Miocene Asmari Limestone, which is the chief reservoir of oil. This theory of migration offers an explanation of the high quality of the Persian oil. According to the alternative hypothesis the oil was formed from the organic matter deposited under lagoon conditions in the Asmari limestones.

In South-eastern Asia a loop from the Himalayan System traverses Western Burma and passes along Sumatra, Java, and the southern side of the Eastern Archipelago. This Burmese-Malayan Arc includes several important oilfields. The Burmese oilfield lies beside the Irrawadi in rocks ranging from the Cretaceous to the Pleistocene. The main oil supply is in the Pegu beds (Oligocene to Miocene); they consist of marine clays containing innumerable pockets and seams of sand in which the oil has collected. Adjacent wells pass through strikingly different beds, and usually do not interfere with one another. The oil is gradually drained from the porous lenticles. The chief oilfield, Yenangyaung, obtains its supply from an area of about 1 square mile on a broad flat dome. Bores opened gushing wells, but the oil is mainly derived from many small pumped wells. In Sumatra and Java the oilfields occur among volcanic rocks, but the oil appears to come from Kainozoic sediments which have undergone mountain folding, and volcanic heat has distilled their organic matter into oil; the high-grade petrol from one field in Sumatra for years was burnt as the cheapest way of getting rid of it. In Borneo within the Malayan Arc and further from the main folding the oil occurs in Kainozoic rocks with a homoclinal dip. Oilfields of secondary importance occur in China where natural gas and oil have been obtained from salt-wells in the Triassic and Permian red sandstones for salt; some of the wells are 3000 feet deep and took generations to bore.

The continents of Africa and Australia have hitherto yielded no important supplies of oil, except in Egypt, or of natural gas, though a little has been found in Queensland.

OIL SHALE

Oil shale is a clay which on distillation yields petroleum of various grades, usually ranging from asphalt or paraffin through heavy lubricating and fuel oils to the lighter illuminating oil, kerosene, and to petrol and the petrol ethers. Typical oil shale itself contains no oil and only a small proportion is soluble by the ordinary solvents for organic materials and hydrocarbons. Some materials, such as some Californian diatomaceous earth which is impregnated with oil, have been classified as oil shale, and according to Cunningham Craig oil shale is clay which has adsorbed oil from percolating petroleum. True oil shale however contains no petroleum, and the oil obtained from it is produced by destructive distillation of its organic constituents. The oil producing material is a pyro-bitumen, i.e. a material which is altered into bitumen by heat.

Oil shale is classed as a sapropelic coal, as a variety of cannel and is classified as earthy cannel (cf. p. 266).

Ordinary oil shale has a tough leathery texture with sometimes a satiny lustre. It resists weathering, so that it often stands out on cliff faces while adjacent shales break down into mud. It may be cut by a knife like tobacco, and varieties rich in oil when cut curl before the knife and are therefore known as curly shale. The richer varieties can be ignited by a match and burn freely. Microscopic examination shows that the oil shale contains many vegetable remains, spores, grains of wax and resin; the characteristic oil producing constituents are yellow bodies which have been identified as pollen grains, algæ, or spores. In many cases they are secondary bodies, often with a radial structure formed by the redeposition of cellulosic and resinous material.

The working of oil shale founded the mineral oil industry. In 1847 a small seepage of petroleum in the Riddings Colliery in Derbyshire was leased by James Young but the supply soon failed. Young concluded that the oil must have been distilled from a shale, and on heating this material in a retort similar oil was produced. The largest supply of oil by distillation was obtained from torbanite; the first oil works was erected at Bathgate, and treated the torbanite which yielded 120 gallons to the ton.

Young's patents were applied in America and many oil shale works established; they were afterwards used as refineries for the oil from wells. The Scottish work had been preceded by some working of shale at Autun in Southern France. The Torbane Hill mineral was soon exhausted, and oil shales used instead; the richer seams were worked out until in later years the Scottish industry was maintained on shale which yielded less than 20 gallons of oil to the ton. After the opening of the oil wells in America the working of oil shale would have become economically impossible, but for the yield of paraffin wax and sulphate of ammonia, which have at times been more profitable than the oil. The ammonia is formed from the nitrogen in the shale.

The Scottish oil shales occur in the Lower Carboniferous rocks E. of Edinburgh, and are interbedded in a series of sandstones, clays, and limestones, which include about twenty seams of worked oil shale. The beds appear to have been laid down in lagoons containing abundant fossil fish and entomostraca; their tissues and the debris of plants which drifted into the lagoons or grew in them, give rise to oil on distillation. Oil shales are known in many parts of the world; they include the Ordovician shales of Esthonia; Devonian shales of the Eastern States of America; Lower Carboniferous in Scotland; Upper Carboniferous or Permian in New South Wales, Tasmania, South Africa, and France. There are vast deposits of Cretaceous and Eocene age in the Rocky Mountains, especially in Colorado and Utah, and large deposits of rich Pliocene oil shale at Mepale in South-eastern Burma.

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